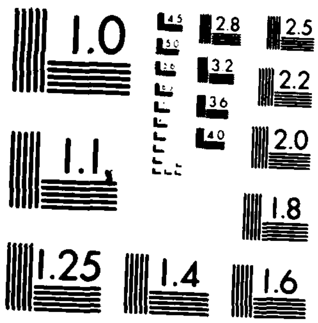
AD-A132 483 TREATMENT OF LANDFILL LEACHATE AT ARMY FACILITIES(U) 1/2
CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAIGN
IL R A SHAFER ET AL. AUG 83 CERL-TR-N-155

UNCLASSIFIED F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

construction
engineering
research
laboratory

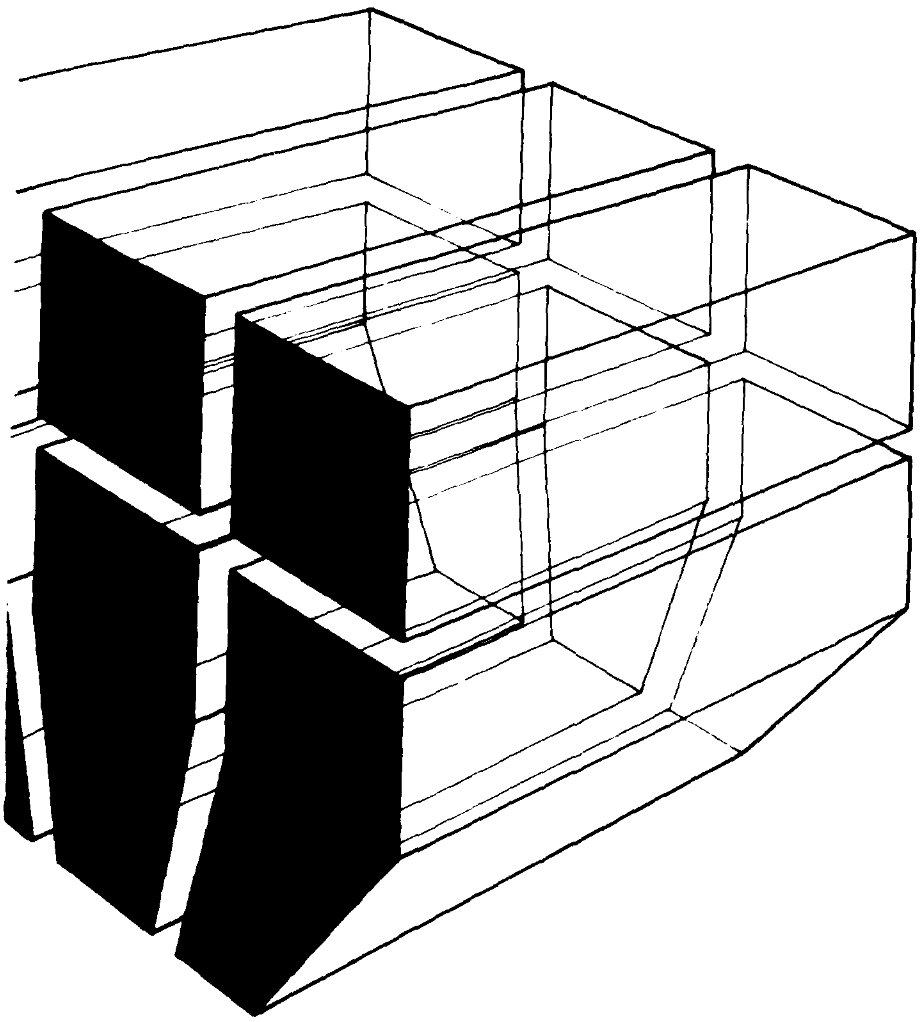
United States Army
Corps of Engineers
Serving the Army
Serving the Nation

Technical Report N-155
August 1983

(Sanitary Landfill Leachate Control at Military Installations)

12

TREATMENT OF LANDFILL LEACHATE AT ARMY FACILITIES



by
R. A. Shafer
E. D. Smith
J. T. Bandy
P. G. Malone
D. A. Moore
L. W. Jones

CERL

Approved for public release; distribution unlimited.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TECHNICAL REPORT N-155	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* TREATMENT OF LANDFILL LEACHATE AT ARMY FACILITIES		5. TYPE OF REPORT & PERIOD COVERED FINAL
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. A. Shafer P. G. Malone E. D. Smith D. A. Moore J. T. Bandy L. W. Jones		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Construction Engineering Research Lab P.O. Box 4005 Champaign, IL 61820		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 4A762720A896-A-033
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE August 1983
		13. NUMBER OF PAGES 131
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* UNCLASSIFLED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

sanitary landfills
leachate

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

There are abandoned land disposal sites (both authorized and unauthorized) and operating facilities at most Army installations. Unless extreme care was taken during location, design, and operation, all land disposal sites can generate a grossly polluted liquid effluent called leachate. This substance is produced by the natural processes which occur between decomposing waste and moisture entering the burial area.

(Cont'd)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

The overall objectives of this research are (1) to supply information allowing Facility Engineers (FEs) at Army installations both to recognize potential or actual leachate problems and to gauge the magnitude of the problems, (2) to provide guidance on short- and long-term remedial actions which might control leachate formation and migration, and (3) to provide information to installation, FE, major command, and district personnel regarding legal ramifications of and responsibilities concerning leachate gas/problems.

The objective of the phase of the study reported here is to provide FEs (1) an overview of the technologies that can be used to treat leachate, and (2) guidance on choosing and designing leachate treatment systems that will meet the Army's needs.

An extensive literature survey identified technologies which have been used to treat leachate, or have shown potential for treating waste with characteristics similar to leachate. Technologies were examined in terms of their operational principles, waste treatment capability, major design and construction parameters, advantages and disadvantages, and estimated costs.

Particular emphasis was given to lagoon technology because it has low capital, operation, and maintenance costs, and it is a form of biological treatment which has shown the most potential for treating typical Army leachates. Existing full-scale-operation lagoons currently treating leachate at Barre, MD, Lowell, MA, and Lycoming, PA, were examined for operational characteristics. An experimental field test was performed at the U.S. Army Engineer Waterways Experiment Station to develop and verify design parameters. Based on this information, design guidance was developed for lagoon treatment of landfill leachate.

FOREWORD

This work was performed for the Directorate of Engineering and Construction, Office of the Chief of Engineers, under RDT&E project 4A762720A896, "Environmental Quality Technology"; Technical Area A, "Installation Environmental Management Strategy"; Work Unit 033, "Sanitary Landfill Leachate Control at Military Installations." The technical monitors were Mr. F. Bizzoco, DAEN-ECE-D, and Mr. R. Newsome, DAEN-ZCF-D. Mr. W. Medding, DAEN-ECE-D, provided advice and assistance.

The investigation was performed by the Environmental Division (EN), U.S. Army Construction Engineering Research Laboratory (CERL) in cooperation with the U.S. Army Waterways Experiment Station (WES). Assistance was provided by Messrs. R. Shafer, P. Malone, L. Jones, A. Green and N. Francingues of WES.

Dr. R. K. Jain is Chief of CERL-EN. COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

CONTENTS

		Page
	DD FORM 1473	1
	FOREWORD	3
	LIST OF TABLES AND FIGURES	5
1	INTRODUCTION	9
	Background	
	Objective	
	Approach	
	Mode of Technology Transfer	
2	OVERVIEW	12
	Regulatory Requirements	
	Leachate Characteristics and Composition	
	Estimation of Leachate Composition and Production Rates	
	Minimizing Leachate Production	
	Leachate Collection	
	Nontreatment Options	
3	AVAILABLE TREATMENT OPTIONS	23
	Physical/Chemical Treatment Options	
	Biological Unit Processes	
	Land Application of Municipal Landfill Leachates	
4	APPLICATION OF AVAILABLE TECHNOLOGY TO LANDFILL LEACHATES	73
	Laboratory Studies	
	Combined Treatment of Leachate and Municipal Sewage	
	Pilot and Full-Scale Studies	
	Land Application Experience	
	Lagoon Treatment of Leachates: Field Experience	
5	CHOOSING A TREATMENT SYSTEM	104
	Biological Treatment Systems	
	Physical/Chemical Treatment Systems	
	Estimating Leachate Treatment Costs	
	Lagoon Treatment of Landfill Leachates -- Design Guidance	
	Design Example for a Single Aerated/Facultative Lagoon	
	Multiple Facultative Lagoon Considerations	
6	CONCLUSIONS	117
	REFERENCES	119
	APPENDIX: Basis of Cost Estimates	125
	METRIC CONVERSION CHART	129
	DISTRIBUTION	

TABLES

Number		Page
1	Composition of Leachates From Control Test Cells and Actual Landfills	14
2	Chemical Characteristics of Nutrient and Organic Fraction of Typical Leachate Samples	15
3	Surface Water Control Techniques for Municipal Landfills	18
4	Groundwater Control Measures at Municipal Landfills	19
5	Leachate Plume Control Techniques	20
6	Summary of Physical/Chemical Leachate Treatment Processes	24
7	Capital and Operating and Maintenance Costs (1976) of Ammonia Stripping in 24-ft Tower, Excluding pH Adjustment	30
8	Inorganic Removal Potential of Activated Carbon	32
9	Summary of Activated Carbon Contacting Methods	34
10	Typical Operating Parameters for Carbon Adsorption Equipment	36
11	Estimated Cost for Tertiary Activated Carbon Leachate Treatment	37
12	Estimated Costs for Chlorinating Effluent From Leachate Treatment Plants	39
13	Common Reactive Groups for Ion Exchange Resin	42
14	Examples of Regenerants and Dosage Ranges for Different Types of Exchange Resins	42
15	Approximate Solubilities of Selected Metals in Water	46
16	Chemical Treatment of Industrial Wastewater by Coagulation	46
17	Construction Cost for Package Complete Treatment Plants Used for Precipitation, Flocculation, Sedimentation, and Filtration	48
18	Operation and Maintenance Summary for Package Complete Treatment Plants Used for Precipitation, Flocculation, Sedimentation and Filtration	49
19	Summary of Biological Leachate Treatment Processes	52
20	Threshold Concentrations for Inhibitory Effects of Various Metals in Aerobic Activated Sludge Processes	55

TABLES (Cont'd)

Number		Page
21	Summary of Operating Parameters for Air-Activated Sludge and Pure Oxygen-Activated Sludge Treatment Systems	57
22	Estimated Construction and Operating and Maintenance Costs for Activated Sludge Treatment Systems	60
23	Examples of Acceptable Loads for Low- and High-Rate Trickling Filters	63
24	Estimated Costs for Trickling Filter Package Plant	63
25	Estimated Construction, Operating, and Maintenance Costs for Rotating Biological Contactors	64
26	Design Criteria for Waste Stabilization Ponds	66
27	Estimated Costs of Different Types of Lagoon Leachate Treatment Systems	67
28	Comparison of Site Characteristics for Land-Treatment Processes	69
29	Comparison of Design Features for Land-Treatment Processes	70
30	Comparison of Expected Quality of Treated Water From Land-Treatment Processes	71
31	Site-Selection Factors and Criteria for Effluent Irrigation	72
32	Characteristics of Leachate, Mixed Liquors, and Effluents From Five Aerobic Digesters	74
33	Characteristics of Leachate, Mixed Liquors, and Filter Effluent From Anaerobic Digesters	76
34	Summary of Performance Characteristics of Various Treatment Processes for Sanitary Landfill Leachate	79
35	Effects of Landfill Leachate Influent Additions on Extended Aeration Sewage Treatment Plant Effluents	80
36	Characteristics of Effluent From Aerated Digester With Sufficient Nutrient Addition	83
37	Configuration No. 1 -- Treatment Performance After Acclimation of Activated Sludge	87
38	Operating and Maintenance Costs for Configuration No. 1 During Both Trial Periods	88

TABLES (Cont'd)

Number		Page
39	Summary of Effects of Configuration No. 2 -- Chemical/Physical Treatment Only	89
40	Operation and Maintenance Costs of Configuration No. 2	90
41	Summary of Effects of Biological Treatment Alone (Configuration No. 4), Followed by Lime Polishing (Configuration No. 3)	91
42	Details of Land Treatment Facilities at Four British Landfills	94
43	Mean Oxygen Demand and Ammonia Levels of the Lagoon Effluents Over the 118-Day Experiment	98
44	Average of Selected Parameters for Both Aerated and Nonaerated Lagoon Series	100
45	Summary of Removal Efficiencies of Bench-Scale Biological Treatment Processes	105
46	A Summary of Cost Estimates for Leachate Treatment	108

FIGURES

Number		Page
1	Clay Barrier and Groundwater Underdrain System	21
2	Ammonia Stripping Lagoon	29
3	Ammonia Stripping Tower	29
4	Most Common Configuration of Activated Carbon Absorber Systems	33
5	Activated Sludge COD Removal Efficiencies for Detention Times of 5 and 10 Days	77
6	Schematic Flow Diagram of GROWS Leachate Treatment Plant: Configuration No. 1	86
7	Schematic Diagram of Martone Aerobic Lagoon Treatment System for Landfill Leachate	95
8	Aerobic Leachate Treatment Lagoons at the Martone Landfill	95
9	Aerated Treatment Lagoon at Lowell, MA Landfill	97

FIGURES (Cont'd)

Number		Page
10	Facultative Treatment Pond to Which Effluent From Aerated Lagoon is Pumped at Lowell, MA.	97
11	BOD Removal Efficiencies for Nonaerated Series of Leachate Treatment Lagoons Over Length of Study at Waterways Experiment Station	99
12	BOD Removal Efficiencies for Aerated Series of Leachate Treatment Lagoons Over Length of Study at WES	99
13	Leachate Study Facilities at WES	101
14	BOD and COD Levels in Closed, Vented Storage Tank (491 Gal) Over 3 Weeks	102
15	Aerated Collector Pond at Lycoming, PA	103
16	Backhoe Digging Trench Through Refuse for Leachate Recycle at Lycoming, PA, Landfill	103

TREATMENT OF LANDFILL LEACHATE AT ARMY FACILITIES

1 INTRODUCTION

Background

Before 1965, there were no effective regulations on the location, design, or operation of municipal garbage dumps, landfills, and industrial waste disposal grounds in the United States. Because of this lack of control, burial of many types of waste material became a widely accepted method of disposal. With few exceptions, Department of the Army (DA) facilities used similar practices.

One difference at DA sites must be stressed: wastes unique to the military have been buried -- e.g., training residues; propellant, explosive, or pyrotechnic residues; and abandoned transformers. Such materials may be mixed with the general solid waste stream and buried in engineered sites; or these wastes may be disposed of separately -- deposited in engineered sites or dumped in locations such as abandoned sand and gravel pits, rock quarries, gullies, hollows, or sink holes.

There are abandoned land disposal sites (both authorized and unauthorized) and operating facilities at most Army installations. Unless extreme care was taken during location, design, and operation, all land disposal sites can generate a grossly polluted liquid effluent called leachate. This substance is produced by the natural processes which occur between decomposing waste and moisture entering the burial area.

When a burial site's moisture-retention capacity is reached, leachate is forced into the surrounding environment, resulting in contamination of groundwater, surface water, and soil. The hazards associated with leachate become especially significant when one considers that only 3.5 oz of the substance (containing toxic metallic, organic, or chlorinated hydrocarbon compound) dissolved in 2.2 million lb of clean water may be harmful or even lethal to humans, animals, plants, and many aquatic life forms.

Leachate pollution is a nationwide concern. The Resource Conservation Recovery Act (RCRA) (Public Law 94-580, October 21, 1976) requires that water supplies be protected from leachate contamination. The U.S. Environmental Protection Agency (EPA) has published comprehensive information on landfill site design, operation, and maintenance, and has described effective means for leachate collection.[1] Current and anticipated Army regulations regarding leachate from operating and abandoned waste disposal sites will significantly

[1] See for example, Handbook for Remedial Action at Waste Disposal Sites, EPA-625/6-82-006 (U.S. Environmental Protection Agency [EPA], June 1982).

affect major command (MACOM), installation, and Facility Engineer (FE) pollution abatement procedures, and associated budgeting.[2]

But one area of concern has not yet been addressed: what are the treatments for Army leachates of varying qualities and ages? The Office of the Chief of Engineers asked the U.S. Army Construction Engineering Research Laboratory (CERL) to examine technologies which already have been evaluated, or which show potential for effective and economical treatment of leachate.

Objective

The overall objectives of this research are (1) to supply information allowing FEs at DA installations both to recognize potential or actual leachate problems and to gauge the magnitude of the problems, (2) to provide guidance on short- and long-term remedial actions which might control leachate formation and migration, and (3) to provide information to installation, FE, MACOM, and district personnel regarding the legal ramifications of and responsibilities concerning leachate problems.

The objective of the phase of the study reported here is to provide FEs (1) an overview of the technologies that can be used to treat leachate, and (2) guidance on choosing and designing leachate treatment systems that will meet the Army's needs.

Approach

An extensive literature survey identified technologies which have been used to treat leachate, or have shown potential for treating waste with characteristics similar to leachate. Technologies were examined in terms of their operational principles, waste treatment capability, major design and construction parameters, advantages and disadvantages, and estimated costs.

Particular emphasis was given to lagoon technology because it has low capital, operation, and maintenance costs, and it is a form of biological treatment which has shown the most potential for treating typical Army leachates. Existing full-scale-operation lagoons currently treating leachate at Barre, MD, Lowell, MA, and Lycoming, PA, were examined for operational characteristics. An experimental field test was performed at the U.S. Army Engineer Waterways Experiment Station to develop and verify design parameters. Based on this information, design guidance was developed for the lagoon treatment of landfill leachates.

---

[2] See for example, W. J. Mikucki et al., Characteristics, Control, and Treatment of Leachate at Military Installations, Interim Report N-97/ADA097935 (U.S. Army Construction Engineering Research Laboratory [CERL], 1981); Environmental Protection and Enhancement, Army Regulation (AR) 200-1 (Headquarters [HQ], Department of the Army [DA], January 20, 1978).

Mode of Technology Transfer

Information developed as a result of this project may impact Army Regulation (AR) 420-47, Solid Waste Management, and Technical Manual (TM) 5-634, Refuse Collection and Disposal (Repairs and Utilities).

2 OVERVIEW

Moisture percolating through landfilled refuse carries dissolved organics and potentially toxic heavy metals out of the refuse. This landfill seepage, or leachate, can seriously contaminate surrounding groundwater or surface water. The contamination sometimes has been so severe that wells near landfills frequently have had to be abandoned as sources of drinking water, and surface waters have been rendered unfit for domestic or recreational use. Typically, leachate pollution is not discovered until fish or plant kills occur in streams or lakes next to a landfill, or seeps of discolored or odorous water are found near the fill. The most permanent and costly damage occurs when the seepage from the landfill pollutes aquifers under the landfill. Damage to water supply wells over a mile from a landfill has been observed.[3] Remedial action is usually not practical, and a new water source often must be provided.

Major cases of water pollution have involved unacceptable changes in water color, taste, and odor, and dangerous levels of nitrate or heavy metals. Although undiluted leachate has been shown to be toxic to the bacteria usually indicating pollution (fecal and nonfecal coliforms), other microorganisms, which may include pathogens, thrive in landfill leachate.[4] Leachate contamination of groundwaters can cause widespread aesthetic, toxicological, and microbial problems.

Regulatory Requirements

Army regulations and technical manuals recognize the problem of landfill leachate production but do not generally address the alternatives for remedial action when uncontrolled landfill drainage is detected.[5] Army facilities are directed to comply with all Federal, State, and locally enforceable regulations and standards regarding pollution of surface water or groundwater from solid waste disposal facilities.

Regulations issued under the RCRA require compliance from all solid waste facilities discharging to surface waters (Section 257.3-3) and groundwaters (Section 257.3-4). Facilities discharging as point sources into surface waters must meet the requirements of the National Pollutant Discharge Elimination System (NPDES) under Section 402 of the Clean Water Act of 1977. A facility discharging as a nonpoint source must follow any applicable legal requirements if it is in the jurisdiction of any areawide or statewide water quality management plan approved under Section 208 of the Clean Water Act. According to Federal regulations on groundwater (e.g., the RCRA), no facility

---

[3] G. A. Garland and D. C. Mosher, "Leachate Effects of Improper Land Disposal," Waste Age (March 1975).

[4] R. D. Cameron and E. C. McDonald, "Coliforms and Municipal Landfill Leachate," Journal, Water Pollution Control Federation (Dec. 1977), pp 2504-2505.

[5] Sanitary Landfill, Technical Manual (TM) 5-814-5 (HQ, DA, 1973); Military Solid Waste Management, NAVFAC MO-213 (Department of the Navy, 1978); Sanitary Landfill, ERIS Bulletin 81-05, TM 5-814-5 (U.S. Army Corps of Engineers, 1981).

may contaminate an underground drinking water source beyond the solid waste boundary. If the State has an EPA-approved solid waste management plan under RCRA, the facility may negotiate an alternate boundary. The maximum contaminant levels permitted in the groundwater correspond to the values allowed under the primary and secondary drinking water standards (Federal Register, CFR 257.3-4, Appendix I). Specific guidance on the applicable Federal regulations is available from the EPA's Office of Water and Waste Management.[6] Local environmental or health agencies must be contacted for specific details on State or county requirements.

Leachate Characteristics and Composition

The major constituents of sanitary landfill leachate are the dissolved organic fractions giving the effluent high chemical oxygen demand (COD), biochemical oxygen demand (BOD), and total organic carbon (TOC). Table 1 lists the values of parameters for leachates produced under controlled laboratory conditions from simulated landfill test cells and provides a range of values from an actual survey of 23 leachates from fills varying in age from 1 to 16 years. COD values typically run from 3 to 10 percent by weight of the leachate. Other organic and nutrient parameters commonly found are total volatile acids (TVA), conductance, alkalinity, total Kjeldahl nitrogen, and total phosphates. Ionic materials of particular importance are chloride, sulfate, calcium, magnesium, iron, sodium, and potassium. Elevated toxic metal levels were noted for aluminum, boron, cadmium, chromium, manganese, and zinc.

A detailed analysis of the organic and nutrient components of four leachates studied by Chian and Dewalle is shown in Table 2.[7] Note the large proportion of short-chain carboxylic acids (two to six carbons) which usually are as much as 90 percent of the total organic content. The even-numbered carbon components (acetic, butyric, and caproic acids) make up the majority. Almost all of the total solids (or total residue) in the leachate are dissolved substances (97.5 to 99.9 percent). There are very few suspended solids. Almost all of the nitrogen is in the form of ammonia or organic amines, as would be expected from the leachate's low oxidation-reduction potential (ORP).

The composition of landfill leachates varies markedly with the age of the landfill. Therefore, leachates are classified by the age of the landfill from which they are produced.[8] Young landfills (generally less than 5 years old) produce leachate with COD greater than 20 000 mg/L, pH values of 5.0 to 6.0, and high metal and anion contents. In addition, BOD usually accounts for over

[6] Classifying Solid Waste Disposal Facilities, A Guidance Manual, SW-828 (U.S. Environmental Protection Agency, 1980), 187 pp; Remedial Action at Waste Disposal Sites (Office of Emergency and Remedial Response, U.S. Environmental Protection Agency), in press.

[7] E. S. K. Chian and F. B. DeWalle, Evaluation of Leachate Treatment; Vol I: Characterization of Leachate, EPA-600/2-77-186a (U.S. Environmental Protection Agency, 1977), 226 pp.

[8] E.S.K. Chian and F. B. DeWalle, "Sanitary Landfill Leachates and Their Treatment," Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers, Vol 102, EE2 (1976), pp 411-429; Evaluation, Vol II.

Table 1

Composition of Leachates From Control Test Cells and Actual Landfills

Parameter*	Control Test Cells**	Field Samples+
Age (months)	8-17	12-193
COD	32 500-76 300	40-89 520
BOD	13 000-25 500	81-33 600
TOC	7000-12 000	256-2800
pH	4.35-5.55	3.7-8.5
Total volatile acids	38-12 000	--
Specific conductance	6000-9800	2810-16 800
Alkalinity	1750-3820	0-20 850
Total Kjeldahl nitrogen	711-902	0-1106 (NH_3)
Total phosphorus	13.6-39.2	0-130
Chloride	867-1442	4.7-2467
Fluoride	<0.01-2.12	--
Aluminum	1.69-6.08	--
Arsenic	<.001-0.045	--
Boron	6.00-9.38	--
Beryllium	<.005	--
Calcium	655-1118	60-7200
Cadmium	0.004-0.028	0.03-17
Chromium	0.089-0.338	--
Copper	0.004-0.030	0-9.9
Iron	229-362	0-2820
Lead	<0.001-0.082	<0.1-2.0
Magnesium	138-178	17-15 600
Manganese	11.0-18.6	0.09-125
Sodium	712-942	60-7700
Nickel	0.268-0.482	--
Potassium	357-615	28-3770
Selenium	0.078-0.160	--
Zinc	6.75-21.7	0-370
Mercury	<0.0002-0.0030	--
Oxidation-reduction potential	(-450)-(-73)	(-220)-(+163)

*All values in mg/L except specific conductance, which is measured as micromhos per centimeter (μmho/cm) pH in pH units, and oxygen-reduction potential in millivolts (mV).

**Leachate from quadruplicate test cells containing 2 tons of wet municipal solid waste (T. E. Myers et al., "Stabilized Industrial Waste in a Landfill Environment," in Disposal of Hazardous Waste; Proceedings of 6th Annual Research Symposium, EPA-600/9-80-010 [U.S. Environmental Protection Agency, 1980]).

+*Leachates from 23 different landfills analyzed* by E.S.K. Chian and F.B. DeWalle, Evaluation of Leachate Treatment; Vol. I: Characterization of Leachate, EPA-600/2-77-186a (U.S. Environmental Protection Agency, 1977); "--" indicates that data are not available.

Table 2

Chemical Characteristics of Nutrient and Organic Fraction of Typical Leachate Samples (From E.S.K. Chian and F. B. DeWalle, Evaluation of Leachate Treatment; Vol I: Characterization of Leachate, EPA-600/2-77-186a [U.S. Environmental Protection Agency, 1977], 226 pp.)

	Landfill Leachate Source (mg/L, except as indicated)			
Parameter	University of Illinois at Urbana-Champaign	Madison, WI	Madison, WI	Cincinnati, OH
Age of landfill (years)	0.25	0.33	0.33	2.3
COD	49 300	1680	16 580	45 750
TOC	17 060	27 700	5906	13 840
BOD	24 700	57 000	9960	22 000
Acetic acid (C2)*	4370	6690	510	1340
Propionic acid (C3)	1050	3180	255	660
Isobutyric acid (C4)	570	360	31	340
Butyric acid (C4)	5620	9270	480	1700
Isovaleric acid (C5)	1220	770	40	520
Valeric acid (C5)	960	1260	265	460
Caproic acid (C6)	2400	1920	565	1090
Bicarbonate alkalinity	668	459	284	175
pH (pH units)	5.63	5.97	5.59	5.25
Conductance (μmho/cm)	13 700	16 800	5420	9450
ORP (mV)	-60	-132	-220	--
Suspended solids	139	202	192	8.9
Fixed suspended solids	92.5	167	110	7.5
Total solids	33 989	55 348	7930	32 145
Fixed solids	15 586	22 348	3475	13 603
Org-nitrogen	544.7	945	78.8	31
NH_4-nitrogen	392.6	1028	347.4	247.7
NO_3-nitrogen	0.5	10.25	4.25	9.8
NO_2-nitrogen	BDL**	0.04	0.04	0.19
Total phosphorus	21.5	98	85	31.6
Ortho-phosphorus	6.5	29	85	28
SO_4	1110	1558	77	090
Cl	1480	2467	474	2096

*Number of carbons.
**BDL -- below detection limits.

half of the COD, and the ratio of COD to TOC is over 2.8. In medium-aged landfills (5 to 10 years old), the COD is lower -- in the range of 500 to 10 000 mg/L. Metal and anion content is also decreased. BOD is between 10 and 50 percent of the COD, and the ratio of COD/TOC is between 2 and 2.8. Old or stabilized landfills are generally over 10 years old and have low CODs (less than 500 mg/L), which consist of less than 10 percent BOD. COD/TOC ratios are less than 2.0. These numbers vary greatly, depending on compaction of the refuse and climatic conditions. More densely compacted waste and refuse landfilled in areas of high temperature and precipitation stabilize (decompose) more rapidly.[9]

The high COD and BOD levels in young leachates are caused primarily by fatty acids of low molecular weight which have chain lengths of two to six carbons (Table 2). This component, which can make up more than 90 percent of the organic content of the leachate, is highly volatile and is rapidly biodegraded under aerobic and anaerobic conditions. As a landfill ages, the relative amount of these short-chain fatty acids rapidly decreases, and a second category of organic substances -- humic carbohydrate-like materials of high molecular weight -- become an important fraction of the organic carbon content. These substances are nonvolatile and are broken down biologically at only moderate rates.

The organic component from old, stabilized landfills is made up largely of refractory fulvic acid-like substances which are only slowly degraded. Even though present in small amounts (generally less than 0.5 percent of the level of the short-chain fatty acids in young landfill leachates), their persistence in the environment can be responsible for a major pollution problem. The biological processes taking place in the landfill itself apparently are responsible for the decrease in the volatile fatty acid component of the leachates as the landfill ages. The remaining -- more refractory -- organics, although present in much lower amounts, are much less amenable to biological treatment and may require physical/chemical treatment procedures to meet discharge requirements.

Estimation of Leachate Composition and Production Rates

Rates of leachate production from sanitary landfills must be estimated before leachate collection and treatment systems can be selected and designed.[10] Comprehensive reports on the use of water budget,[11] the water

---

[9] R. Stegmann and H. J. Ehrig, "Operation and Design of Biological Leachate Treatment Plants," Prog. Water Tech. (Toronto), Vol 12 (1980), pp 919-947.

[10] Pollution Predicting Technique for Waste Disposal Siting, EPA-SW-162c (U.S. Environmental Protection Agency, 1978), 440 pp; D. R. Brunner, "Forecasting Production of Landfill Leachate," Municipal Solid Waste: Land Disposal, Proceedings, 5th Annual Research Symposium, EPA-600/9-79-023a (U.S. Environmental Protection Agency, 1979), pp 268-282.

[11] J. R. Mather and P. A. Rodriguez, The Use of the Water Budget in Evaluating Leachate Through Solid Waste Landfills, #PB 80-18088 (Office of Water Research and Technology, U.S. Department of Commerce, 1978), 39 pp.

balance method,[12] and hydrologic modeling[13] provide detailed methods of leachate production-rate estimation. Although leachate quality varies over wide ranges, useful leachate strength estimates have been suggested by an extensive study of many landfills.[14] Stegmann and Ehrig found that the most important factor controlling the quality of leachate production from landfills of comparable ages was the density of the implaced refuse. Leachates from low-density, compacted landfills usually have BODs approximately one-half (averaging 7500 mg/L) those of high-density refuse (generally around 15 000 mg/L). Amounts of leachate being produced by existing unlined landfills can only be accurately determined by field data at the actual site since unknown losses to, and mixing with, surface water and groundwaters can change estimates of leachate quality and quantity by orders of magnitude.

Minimizing Leachate Production

Several management techniques can be used to lessen the volume of landfill leachate which must be treated. The entry of surface waters into the landfill can be limited by sealing the surface with an impervious or low permeability cover such as clay or plastic membrane; by diverting surface waters or using contour grading to encourage runoff; and by planting vegetation to increase evapotranspiration and lessen erosion of the covering materials.[15] These options are compared in Table 3. For every gallon of water kept out of the fill, one less gallon of leachate must be treated.

When the waste mass is buried below the water table, only major construction can keep out groundwater. The expense of these techniques generally restricts their use to the most critical cases of pollution. Possible measures for controlling groundwater are diverting or blocking its flow into the landfill by construction of clay barriers and groundwater underdrainage systems (Figure 1), by installation of a slurry trench, by injection of a grout curtain, or by installation of sheet-piling up the groundwater gradient from the landfill. Bottom sealing of an existing landfill site using grout injection wells is another option, but it is expensive. Active pumping of groundwater to control the water table below a site has been used temporarily in particularly difficult locations. Pumping is only suitable in emergencies until the wastes can be destroyed or moved to a secured site.[16] Groundwater control measures are summarized in Table 4, and some leachate plume control techniques are listed in Table 5.

---

[12] D. G. Fenn et al., Use of Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites, EPA-530/SW-168 (U.S. Environmental Protection Agency, 1975).

[13] E. R. Perrier and A. C. Gibson, Hydrological Simulation on Solid Waste Disposal Sites, SW-868 (U.S. Environmental Protection Agency, 1980), 111 pp.

[14] R. Stegmann and H. J. Ehrig.

[15] R. J. Lutton, G. L. Regan, and L. W. Jones. Design and Construction of Covers for Solid Waste Landfills, EPA-600/2-79-165 (U.S. Environmental Protection Agency, 1979), 249 pp.

[16] J. Wardell et al., "Contamination Control at Rocky Mountain Arsenal, Denver, Colorado," in Management of Uncontrolled Hazardous Waste Sites (Silver Springs, MD: Hazardous Materials Control Research Institute, 1981), pp 374-379.

Table 3

Surface Water Control Techniques for Municipal Landfills
(Adapted from J. C. S. Lu, et al., "Leachate Production and Management From Municipal Landfills: Summary and Assessment," Land Disposal: Municipal Solid Waste, EPA-600-9/81-002a [U.S. Environmental Protection Agency, 1981], pp 1-17.)

Control Techniques	Optimum Site Conditions	Limitations	Economics	Perceived Effectiveness
Contour grading and surface water diversion	Landfill stabilized; sufficient borrow area for soil excavation available nearby.	Available soil cover should be present. Differential settlement is extensive, requiring large volumes of soil.	\$126,000 to \$242,000 for a 10-acre landfill.	An effective control measure used both during landfilling and once the fill has been stabilized.
Surface sealing	Borrow material available; landfill has been stabilized and/or graded.	Suitable cover material may not be readily available. Gas venting may also be required.	\$140,000 to \$256,200 for a 10-acre site.*	Effective if settlement is minimal and when used with other control measures.
Revegetation	Stabilized fill and available cover soil (>2 ft). Minimum of settlement and gas control equipment available at the site.	Decomposition gases may be toxic to vegetation if not vented or controlled.	12¢ to 18¢ per acre.	Provides a buffer to moisture entering the fill and reduces erosion. Is most effective when used with several control measures.

*Based for a clay cap 6-in. thick; assumes earthmoving costs of \$1000/acre.

Table 4

Groundwater Control Measures at Municipal Landfills (Adapted from J. C. S. Lu et al., "Leachate Production and Management From Municipal Landfills: Summary and Assessment," in Land Disposal: Municipal Solid Waste, EPA-600-9/81-002a [U.S. Environmental Protection Agency, 1981], p 1-17.)

Control Technique	Optimum Site Conditions	Limitations	Costs
Artificial liner	Groundwater near the refuse/soil interface, Underlying soils have a moderately rapid to very rapid permeability 1.4 x 10^{-3} cm/sec to >1.4 x 10^{-2} cm/sec.	Requires installation before landfilling. Expected life not established. Rising groundwater may cause rupture of the liner. May be damaged during landfilling activities. Once installed, extremely difficult to repair.	$1.00 to $5.00 per installed sq yd.
Bottom sealer	Same as for artificial liner, and when detailed information about the soil is available.	Detailed understanding of soil properties is required. Only practical before landfilling.	$1.20 to $2.00 per installed sq yd.
Slurry trench	Groundwater and bedrock near the surface. Other conditions similar to those for an artificial liner.	Costs of shipping bentonite. Excavation difficult due to soil conditions. Bentonite may deteriorate when exposed to high strength leachate.	$294 to $495 per installed linear foot.
Grout curtain	Same as for an artificial liner; bedrock near the surface.	Considered effective in soils with permeabilities >10^{-5} cm/sec. Costs may be prohibitive for large-scale use. Difficult to assess the integrity of the seal.	$142 to $357 per installed cu yd.
Sheet piling cutoff wall	Same as for grout curtain.	Corrosion potential is high, and problems with driving the sheet through rocky soils are common. Ability to maintain integrity of the piling is questionable.	$382 to $562 per installed linear foot.

Table 5

Leachate Plume Control Techniques
(Adapted from J. C. S. Lu et al., "Leachate Production and Management From Municipal Landfills: Summary and Assessment," in Land Disposal: Municipal Solid Waste, EPA-600-9/81-002a [U.S. Environmental Protection Agency, 1981], p 1-17.)

Control Technique	Optimum Site Conditions	Limitations	Economics	Perceived Effectiveness
Drains	Near-to-surface groundwater; soils which are easily excavated; consistent groundwater level with little fluctuation.	Groundwater may be too deep for effective use of drains. Soils may not be easily excavated. Area required may be too large for practical drainage.	$300-$800/acre	Effective when used with other control approaches such as liners, well points, etc.
Well point system	Same as for drains.	Usually effective for shallow dewatering (<10 m).	Capital cost, $1.33 per linear foot. Maintenance and operational costs; $1.67 per linear foot.	Effective when used to complement another control system.
Deep well system	There is more water than a well point system may withdraw.	Capable of withdrawing about 40 vertical feet of water in uniform sands.	Capital cost $18,000 to dewater 900 linear feet. Maintenance and operational costs, $10,500/year.	Effective in radically altering the hydraulic gradient in a small area.

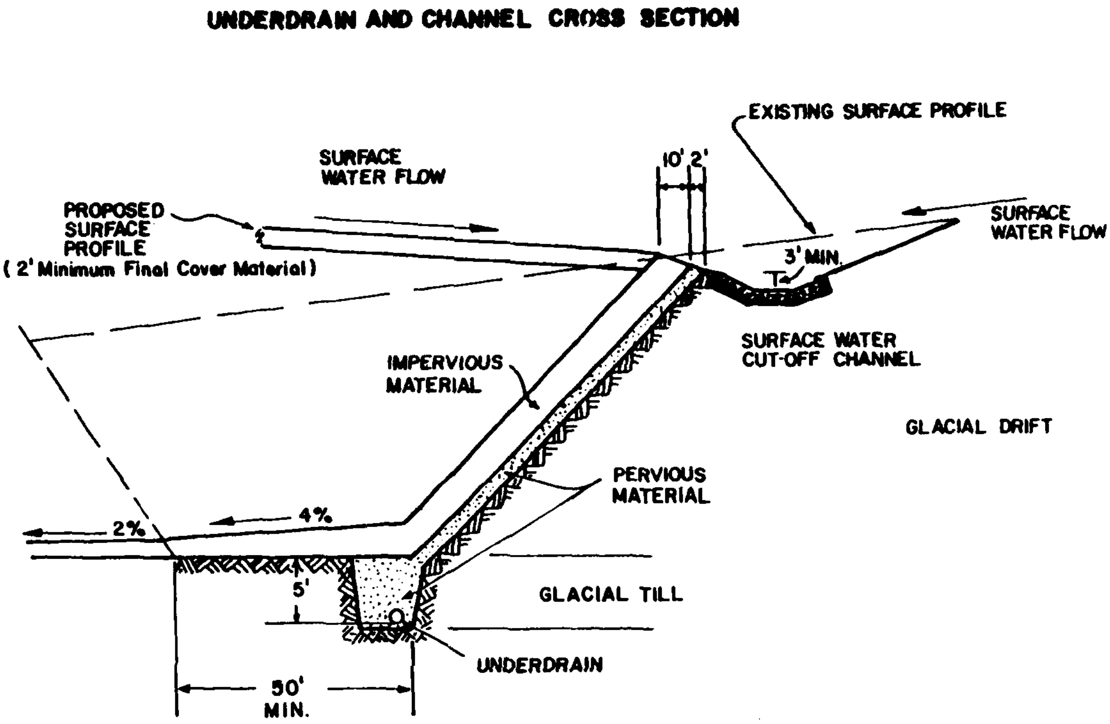


Figure 1. Clay barrier and groundwater underdrain system.

Leachate Collection

Adequate liners and facilities for leachate collection and monitoring must be provided at landfills now being developed where leaching is probable. However, existing landfills seldom have such facilities; remedial collection methods must be developed for each site. Commonly installed leachate collection systems include interceptor trenches, toe drains, and collection wells.[17] Collection of leachate before it is diluted by mixing with groundwater or surface water makes treatment much easier, but is not always possible.

Nontreatment Options

Dilution and Attenuation

No bottom control or leachate collection and treatment is necessary in two cases: when the groundwater cannot be used as a drinking water or domestic supply source and therefore does not need to be protected; and when the

[17]For information on design and installation of remedial collection systems refer to Remedial Action at Waste Disposal Sites; A. Metry and F. L. Cross, Leachate Control and Treatment; Vol 7: Environmental Monograph Service, Westport, CT (Technomic Publ. Co., 1975), 58 pp.

site's hydrogeologic conditions reduce the leachate's impact on the underlying groundwater.[18] Thus, the pollutants are attenuated in naturally occurring soil layers, and the leachate in the natural aquifer is so dilute that it presents no problems. Any factors which reduce the rate of infiltration into the landfill also increase the chances that a nontreatment option might be possible. Facilities should consider relying on soil attenuation mechanisms if, given the soil conditions, it can be shown that the leachate will not be a threat to the environment nor to human health.

Extensive studies have been done on soil minerals' attenuation of constituents of landfill leachates.[19] In general, soils may adsorb low concentrations of some heavy metals, but have little or no effect on the high levels of organic materials or soluble salts such as chlorides or sulfates. Dilution and attenuation appear to be useful options only in exceptional circumstances. Thus, leachate collection and treatment will probably become a legal requirement for landfills.

Transport to Municipal Sewage Treatment Plants

Adding leachate to a municipal sewage treatment plant stream is frequently the most economical solution to landfill leachate problems.[20] Sewage treatment plants can accept up to 2 to 5 percent by volume of high strength leachate without adverse effects.[21] Although the treatment fees can be significant, the reduction of the need for onsite personnel or onsite treatment facilities makes use of municipal sewage treatment facilities an attractive option. Often the largest part of the cost is transporting the leachates to the treatment plant if no sewage lines are near the fill. In some cases, high-strength leachates are being transported long distances in tank trucks.[22] Convincing treatment plant authorities to accept leachates into their influent is becoming less difficult as this practice grows more common and experience with treating landfill leachates becomes more widespread.

---

[18] R. A. Landon, "Utilization of a Mixing Zone for Leachate Management," Land Application of Residual Materials, American Society of Civil Engineers (1979), pp 90-103; W. A. Pettyjohn et al., "Predicting Mixing of Leachate Plumes in Groundwater," in Land Disposal of Hazardous Waste, EPA-600/9-82-002 (U.S. Environmental Protection Agency, 1982), 549 pp.

[19] P. M. Malone and L. W. Jones, Chemical and Physical Effects of Municipal Landfills on Underlying Soils and Groundwater, EPA-600/2-78-096 (U.S. Environmental Protection Agency, 1978), 154 pp; R. A. Griffin and N. F. Shimp, Attenuation of Pollutants in Municipal Landfill Leachate by Clay Minerals, EPA-600/2-78-157 (U.S. Environmental Protection Agency, 1978), 157 pp; W. H. Fuller, Investigation of Landfill Leachate Pollution Attenuation by Soils, EPA-600/2-78-158 (U.S. Environmental Protection Agency, 1978), 239 pp.

[20] M. P. Scott, "Leachate Treatment Options," Solid Waste Management (December 1981), pp 18-24.

[21] Estimating Waste Treatment Costs, Vol 3: Cost Curves Applicable to 2,500 gpd to 1.0 mgd Treatment Plants, EPA-600/2-79-162c (U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, 1979); E. S. K. Chian and F. B. DeWalle, Vol II; M. D. Cummins, "Effect of Sanitary Landfill Leachate on the Activated Sludge Process," Land Disposal: Municipal Solid Waste, Proceedings of 7th Research Symposium, EPA-600/9-81-002a (U.S. Environmental Protection Agency, 1981), pp 170-178.

[22] M. P. Scott.

3 AVAILABLE TREATMENT OPTIONS

Development of treatment options for landfill leachates has been based largely on sewage treatment technology. This chapter summarizes sewage treatment unit operations which have been suggested or tested for treatment of landfill leachate. These options are broken into categories based on whether they are largely physical/chemical or biological. Each treatment option is discussed in terms of its applicability to various waste types and strengths, major design and construction parameters, advantages and disadvantages, and estimated costs.

The cost estimates in this chapter have been adapted from several sources (see the appendix). Most costs are 1976 figures from recent EPA publications.[23]

Physical/Chemical Treatment Options

In the treatment of wastewater, physical/chemical unit processes change the waste stream by application of physical forces or by chemical reaction. Physical unit processes are generally subtractive, in that there are fewer dissolved constituents after treatment than before. Chemical unit processes, on the other hand, are additive -- i.e., in most cases, something is added to remove something else. As a result, chemical unit processes produce a net increase of dissolved constituents in wastewater. For example, when chemicals are added to improve removal efficiency, the total dissolved solids (TDS) concentration is always increased. Another disadvantage of chemical unit processes is that generally they are expensive.

Table 6 describes physical/chemical unit processes which are being investigated or have been suggested for use in leachate treatment systems. The table is not all-inclusive and is directed specifically toward treatment of landfill leachates. Each option in the table is discussed in more detail below.

Ammonia Stripping

Ammonia stripping is a mass transfer operation in which pH of the waste material is adjusted by base addition, and the solution aerated to free it of ammonia gas. At pH 12, all ammonia in solution exists as free ammonia, as shown in the equation below:

$$NH_4^+ \xrightarrow{+ (OH)^-} NH^3 + H_2O \qquad [Eq\ 1]$$

The free ammonia gas is stripped from the solution by aeration or spraying.

Ammonia stripping should be used on any leachate that has ammonia in concentrations high enough to be toxic to biomass in subsequent biological

[23] *Estimating Waste Treatment Costs*, Vol 3; *Remedial Action at Waste Disposal Sites*, in press.

Table 6

Summary of Physical/Chemical Leachate Treatment Processes
(Adapted from B. G. Liptak, ed., Environmental Engineer's Handbook, Vol I: Water Pollution [Chilton Book Co., 1974]; Selected Biodegradation Techniques for Treatment and Ultimate Disposal of Organic Materials, EPA-600/2-79-006 [U.S. Environmental Protection Agency, 1979]; D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes [Noyes Data Corp., 1978]; M. J. Hammer, Water and Wastewater Technology [John Wiley & Sons, 1975].)

Treatment Method	Feed Stream Requirements and Limitations	Major Design and Performance Criteria	Environmental Impact	Technology Status	Reliability
Ammonia stripping	Relatively insensitive to concentration changes Requires pH of 10.8 to 11.5 Not operable at freezing temperatures	Hydraulic load pH Temperature Air flow Tower packing and depth	May result in air pollution by NH_3 or volatile organics; not a problem if recovery is implemented	Fully demonstrated but now widely used	High if proper pH is maintained
Carbon adsorption	More amenable to treatment of certain classes of organics Treat organics to an upper limit of about 10,000 ppm TOC Oil and grease should be less than 10 ppm Suspended solids should be less than 50 ppm Where organics are being removed concentrations of less than 500 ppm are advisable	Organic load Hydraulic load Contact time Regeneration and backwash requirements	May be emissions from thermal regeneration, but these can be controlled with scrubbers or afterburners; where there is no regeneration, disposal of spent carbon can be hazardous	Highly developed and widely used	Moderate depending on design and equipment quality; insensitive to toxics but subject to clogging with high suspended solids, oil, and grease; isotherms may give artificial results of process performance

Table 6 (Cont'd)

Treatment Method	Feed Stream Requirements and Limitations	Major Design and Performance Criteria	Environmental Impact	Technology Status	Reliability
Chemical oxidation (chlorination, ozonation)	pH and temperature dependent Organic loading limitations	Temperature and pH Contact time Mixing Presence of interfering compounds	Can cause formation of chlorinated organics and release of chlorine gas or ozone, both of which are toxic	Fully developed and widely used	High; operation is simple
Flow equalization	Can accept any waste fluctuations for which it was designed	Hydraulic flow and variations in flow Detention time Mixing Aeration	Generates sludge; potential for evaporation of volatile wastewater components	Fully demonstrated and widely used	Very high; easily designed to obtain objectives
Ion exchange (solid)	Because of regeneration requirements, concentration should be <2500 ppm or 0.5 equivalents/L; may accept up to 4000 ppm Suitable for treatment of all soluble metal cations or anions, anionic halides, cyanides, nitrates, and some acids	Waste type and load Hydraulic load Mode of operation Regeneration requirements Resin adsorption capacity	Generates a highly concentrated regeneration solution that must be treated	Fully developed but not widely used	Moderate for mixed bed; and air for continuous systems requires a high degree of monitoring and inspection

Table 6 (Cont'd)

Treatment Method	Feed Stream Requirements and Limitations	Major Design and Performance Criteria	Environmental Impact	Technology Status	Reliability
Liquid ion exchange	Volume of extractants required places a practical upper limit of about 10 g/L Sensitive to oxidants, surfactants, and suspended solids Suitable for treatment of anions, cations, metal oxyanions, and weak acids	Waste type and load Hydraulic load Mode of operation Regeneration requirements	Generates a highly concentrated regeneration solution; also, clean stream may contain low concentrations of organic phase that should be removed	Fairly well developed but rarely used, especially for dilute waste streams	Moderate; process is complex and not well-documented
Precipitation/ flocculation/ sedimentation	No concentration limit Sensitive to hydraulic and waste load fluctuation	Hydraulic load Concentrations of suspended solids and precipitable soluble species pH; alkalinity Settling rate Removal requirements for subsequent treatment processes	Generates large amounts of sludge, some of which is difficult to dewater	Highly developed; widely used	Moderate; effluent quality may vary considerably; would require frequent use of jar test to determine appropriate concentrations of flocculants and precipitants

Table 6 (Cont'd)

Treatment Method	Feed Stream Requirements and Limitations	Major Design and Performance Criteria	Environmental Impact	Technology Status	Reliability
pH adjustment	Amenable to wide range of conditions	Waste type and load Detention time Mixing	May generate high concentrations of solids	Highly developed; widely used	Very high, assuming waste stream characteristics are unstable
Reverse osmosis	Requires low solids and organics Readily oxidizable materials promote membrane clogging	Waste type and loading Back wash requirement Subsequent treatment of concentrated waste streams Control of biological activity	Produces high strength waste stream that must be treated or recycled	Demonstrated for low volume of high quality effluent	Moderate. Dependent on type of feed stream
Wet air oxidation	Solution of any organics can be oxidized if temperature and pressure are high enough	Temperature Residence time Waste COD	Process is very clean and generates no air pollution	Relatively new process and not fully demonstrated	Process reliability has not been adequately tested, process is complex and requires use of controls

treatment. Leachate from municipal refuse can have widely varying ammonia concentrations. A range of 2 mg/L to about 1000 mg/L has been reported for leachate from 13 municipal fills.[24] Consideration should also be given to diluting the leachate to reduce BOD levels before biological treatment; this may reduce the toxicity of both ammonia and high BOD concentration, and may make ammonia stripping unnecessary.[25]

Ammonia stripping can be done either in a stripping lagoon or in a packed column (Figures 2 and 3). The major factors affecting performance and design include pH, temperature, air flow, hydraulic loading, and tower packing depth and spacing. Cost and performance are relatively independent of influent ammonia concentrations.[26] The pH must be raised so that all or nearly all ammonia is converted to gas. The pH for efficient operations varies from about 10.8 to 11.5. When lime precipitation is part of a treatment scheme, ammonia stripping should be done after lime precipitation to take advantage of the high pH in the clarifier effluent. As the water temperature decreases, removing ammonia by stripping becomes more difficult. The amount of air per gallon must be increased to maintain removal as temperature decreases. The best hydraulic load for a packed tower is about 1 to 2 gpm/sq ft. Air flow rates for packed towers should be 300 to 500 cu ft/gal for 90 to 95 percent removal. When ammonia concentrations are high (over 100 mg/L), it may be attractive both economically and environmentally to recover the ammonia in an adsorption tower. With good countercurrent contact, 90 to 95 percent of the ammonia can be transferred to the absorption solution.

Ammonia stripping is advantageous because it can reduce ammonia to levels that are not toxic to biomass in biological treatment. In addition, the process is relatively independent of ammonia concentration.

Disadvantages include its high cost to operate at temperatures below freezing; its sensitivity to pH, temperature, and fluxes in hydraulic load; and its release of ammonia to the air, which may create an environmental problem unless the ammonia is recovered.

Construction costs for a stripping tower are moderate. Table 7 gives the cost for constructing, operating, and maintaining a packed tower. The table includes engineering, legal, fiscal, and finance costs during construction, but excludes the cost of pH adjustment. (Costs are based on 1 gpm/sq ft of column packing of 24-ft depth.)

Carbon Adsorption

Carbon adsorption involves contacting a waste stream with carbon, which selectively adsorbs hazardous materials by physical or chemical forces. When carbon reaches its ultimate capacity for adsorption -- that is, when rate of adsorption and desorption are equal -- the carbon is removed for disposal, destruction, or regeneration.

---

[24]E. S. K. Chian and F. B. DeWalle, Vol II.
[25]E. S. K. Chian and F. B. DeWalle, Vol II.
[26]R. L. Culp et al., Handbook of Advanced Wastewater Treatment (Van Nostrand Reinhold Co., 1978).

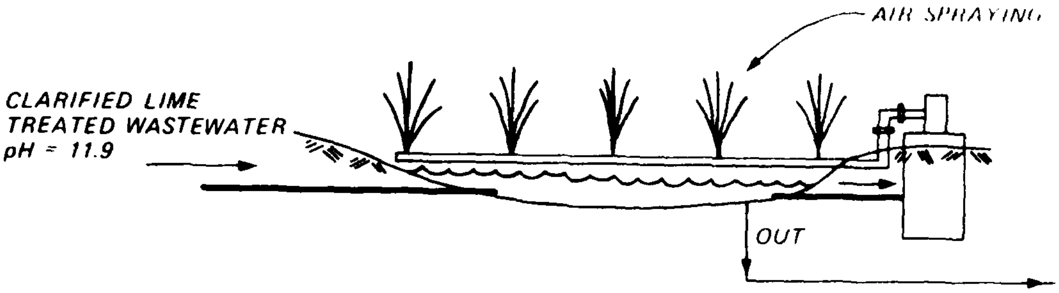


Figure 2. Ammonia stripping lagoon. (From R. L. Culp et al., Handbook of Advanced Wastewater Treatment [Van Nostrand Reinhold Co., 1978].)

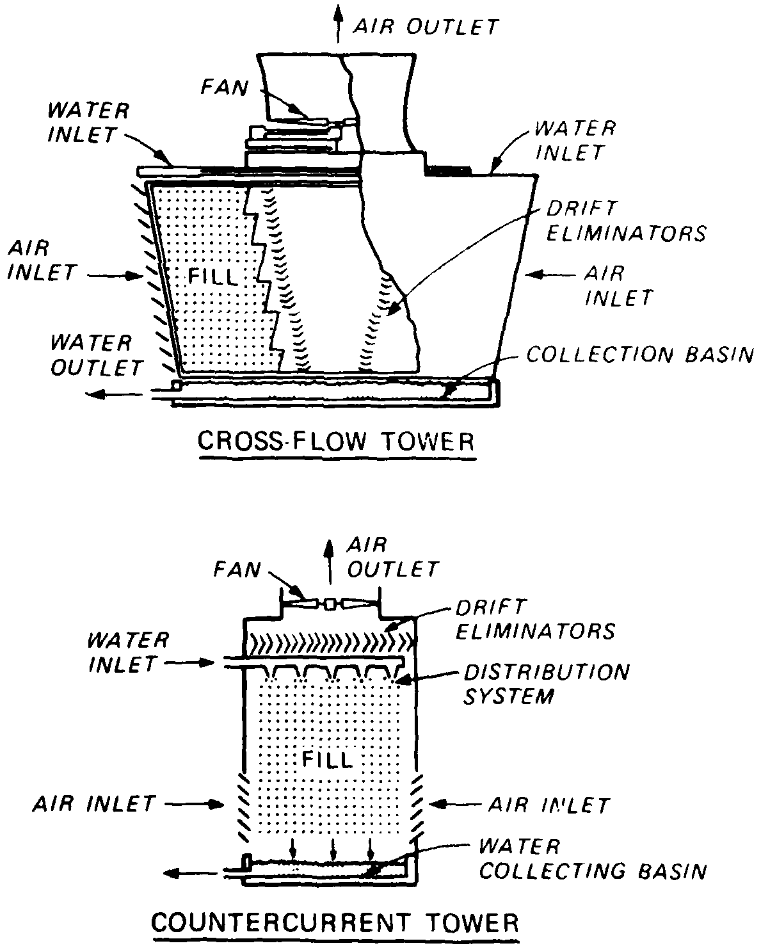


Figure 3. Ammonia stripping tower. (From R. L. Culp et al., Handbook of Advanced Wastewater Treatment [Van Nostrand Reinhold Co., 1978].)

Table 7

Capital and Operating and Maintenance Costs (1976) of Amonia Stripping in 24-ft Tower, Excluding pH Adjustment

Flow, mgd	Construction Cost, $	Operation and Maintenance Cost, $
0.01	4,800	2,200
0.1	37,000	5,500
0.3	100,000	8,000
0.6	180,000	11,000
1.0	300,000	14,500

The suitability of carbon adsorption for treating wastewater from disposal sites depends on the influent characteristics, the extent of pretreatment, and the required effluent quality. The highest concentration of solute in the influent stream that has been treated on a continuous basis is 10,000 ppm TOC, which is now considered the upper limit for the process.[27]

Concentrations of oil and grease in the influent should be limited to 10 ppm. Concentrations of suspended solids should be less than 50 ppm in upflow systems; downflow systems can handle concentrations as high as 2000 ppm, although backwashing is required. Removal of inorganics by carbon generally requires concentrations of less than 1000 ppm, and preferably less than 500 ppm.[28]

The use of activated carbon to remove certain solutes depends on their molecular weight, structure, and solubility. The effects of organics' molecular structure and other properties on their absorbability is summarized below.[29]

---

[27]D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes (Noyes Data Corp., 1978).
[28]D. H. De Renzo.
[29]Hardam Azad, ed., Industrial Wastewater Management Handbook (McGraw-Hill, 1976).

1. Aromatic compounds are generally more adsorbable than aliphatic compounds of similar molecular size.

2. Branched chains are usually more adsorbable than straight chains.

3. Substituent groups affect adsorbability:

Substituent group	Nature of influence
Hydroxyl	Generally reduces adsorbability; extent of decrease depends on structure of host molecule.
Amino	Effect similar to that of hydroxyl but somewhat greater. Many amino acids are not adsorbed appreciably.
Carbonyl	Effect varies according to host molecule; glyoxylic acid more adsorbable than acetic, but similar increase does not occur when introduced into higher fatty acids.
Double bonds	Variable effect.
Halogens	Variable effect.
Sulfonic	Usually decreases adsorbability.
Nitro	Often increases adsorbability.

4. An increasing solubility of the solute in the liquid carrier decreases its adsorbability.

5. Generally, strongly ionized solutions are not as adsorbable as weakly ionized ones; i.e., undissociated molecules are, in general, preferentially adsorbed.

6. The amount of hydrolytic adsorption depends on the capability of the hydrolysis to form an adsorbable acid or base.

7. Unless the screening action of the carbon pores intervenes, large molecules are more sorbable than small molecules of similar chemical nature. This is attributed to more solute/carbon chemical bonds being formed, making desorption more difficult.

Activated carbon effectively removes a variety of chlorinated hydrocarbons, organic phosphorus, carbonates, polychlorinated biphenyls (PCBs), phenols, and benzenes. Specific hazardous organics that are effectively removed include aldrin, dieldrin, endrin, DDD, DDE, DDT, and toxaphene.[30] The activated carbon's potential to remove selected inorganic ions is shown in Table 8. Activated carbon treatment has not been shown suitable for treating leachates from young municipal landfills; carbon shows poor adsorption capacity for fatty acids, which are prevalent in municipal landfill leachate. Carbon adsorption is generally not effective for wastes with high BOD/COD and COD/TOC ratios.[31]

Critical design criteria are organic load, hydraulic load, contacting method, contact time, and regeneration requirements. The approximate carbon

---

[30] R. L. Culp et al.

[31] E. S. K. Chian and F. B. DeWalle, Vol II.

Table 8

Inorganic Removal Potential of Activated Carbon
(Adapted from R. L. Culp et al., Handbook of Advanced Wastewater Treatment [New York, New York: Van Nostrand Reinhold Co., 1978].)

Constituent	Sorption Potential	Potential for Removal by Activated Carbon
Antimony	Very good	Highly sorbable in some solutions
Arsenic	Very good	Good removal in higher oxidation states
Barium	Poor	Very low
Beryllium	Unknown	Unknown
Cadmium	Poor	Slight
Chromium	Very good	Good, easily reduced
Cobalt	Good	Trace amounts readily sorbed
Copper	Poor	Slight, unless complexed
Iron	Fair	Ferric good, ferrous poor
Lead	Fair	Good
Manganese	Unknown	Perhaps as MnO_4
Mercury	Good	Metal filtered out, organic forms good
Molybdenum	Poor	Slight at pH 6 to 8, good if complexed
Nickel	Fair	Fair
Selenium	Poor	Slight
Silver	Good	Reduced on carbon surface
Tin	Good	Very high
Titanium	Fair/good	Good
Tungsten	Poor	Slight
Zinc	Poor	Slight
Phosphate		Not sorbed but may precipitate
Chlorine, bromine		Strongly sorbed and reduced
Chloride, bromide		Not appreciably sorbed

requirements for a specific organic load, and the residual organic levels can be estimated from adsorption removal kinetics conducted on a batch basis. An isotherm can be used as a functional expression for variation of adsorption with concentration of adsorbate bulk solution. The isotherm is expressed in terms of removal of impurity (i.e., BOD, COD, or color).

$$\frac{X}{M} = (KC)^{1/n} \qquad \text{[Eq 2]}$$

where:
X = impurity adsorbed
M = weight of carbon required
C = equilibrium concentration of impurity
K,n = constants.

Isotherms are a useful approximation of treatability, but generally give a falsely high estimate of continuous carbon performance.

Waste streams can be contacted in four basic ways. The method chosen depends on influent characteristics, effluent criteria, flow rate, and economics. Table 9 summarizes these methods, which are illustrated in Figure 4.

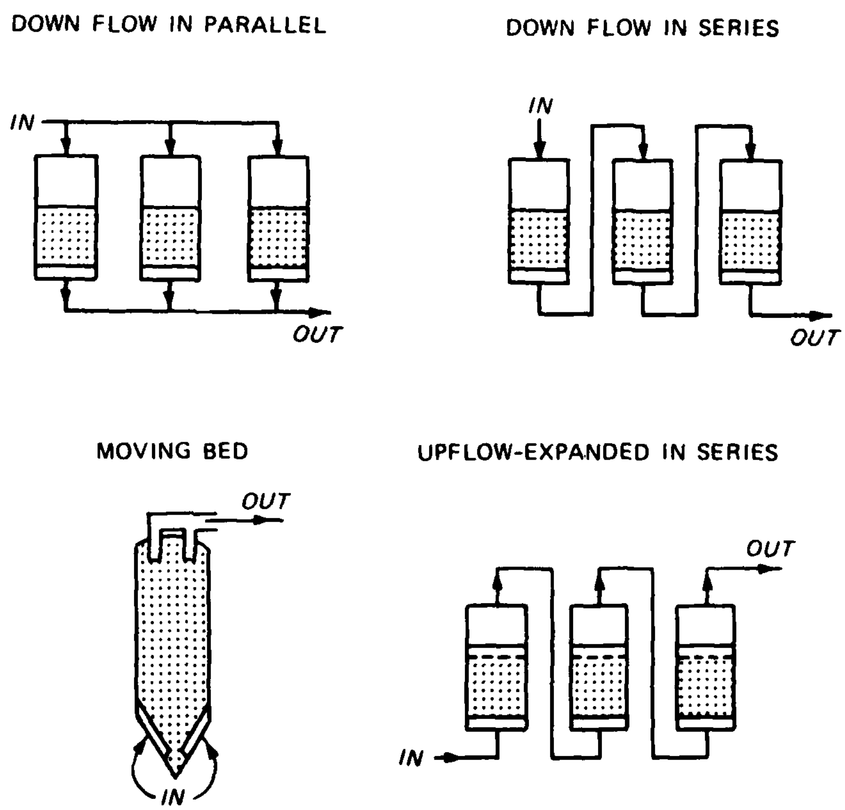


Figure 4. Most common configuration of activated carbon absorber systems.

Table 9

Summary of Activated Carbon Contacting Methods
(Adapted from D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes [Park Ridge, NJ: Noyes Data Corporation, 1978].)

Absorber Configuration	Comments
Downflow adsorbers in parallel	For high volume applications
	Can handle higher than average suspended solids (~ 65 to 70 ppm)
	Relatively low capital costs
	Effluents from several columns blended, therefore less suitable where effluent limitations are low
	2 to 10 gpm/sq ft flow rate
Downflow adsorbers in series	Large volume systems
	Countercurrent carbon use
	Effluent concentrations relatively low
	Can handle higher than average suspended solids (~ 65 to 70 ppm) if downflow
	Capital costs higher than for parallel systems
	2 to 10 gpm/sq ft flow rate
Moving bed	Countercurrent carbon use (most efficient use of carbon)
	Suspended solids must be low (<10 ppm)
	Capital and operating cost relatively high
	Can use such beds in parallel or series
	2 to 7 gpm/sq ft flow rate
Upflow-expanded in series	Countercurrent carbon use (if in series)
	Can handle high suspended solids (they are allowed to pass through)
	High flows in bed (~ 15 gpm/sq ft)
	Minimum pretreatment
	Minimum head loss

Upflow beds have the following advantages over downflow beds; they more closely approach continuous countercurrent contact operations, which results in minimal use of carbon; they can be designed to allow removal of spent carbon and addition of fresh carbon while the columns remain in operation. However, downflow beds can handle higher suspended solids concentrations, although frequent backwashing may be needed.

Typical operating parameters for carbon adsorption systems are summarized in Table 10. The parameters are based on system operations for physical/chemical and tertiary treatment systems.

The decision about whether to regenerate and reuse granular carbon or to use it once depends primarily on economics. For plants requiring less than 200 lb/day of carbon (less than approximately 0.8 mgd flow rate), regeneration is probably not economical. Most leachate treatment facilities will fall within this range. Use of electric furnaces, rather than multiple hearth furnaces, may make it possible to regenerate activated carbon economically for plants using less than 200 lb/day.[32] Regeneration needs can be determined on the basis of COD adsorbed per pound of carbon, or required carbon dosage in terms of total flow.

Advantages of activated carbon over other treatment options are: (1) flexible operation and design; (2) suitable for treatment of a wide range of organics that do not respond to biological treatment; (3) high adsorption potential for some highly toxic inorganics (i.e., Cr, CN); and (4) tolerant of fluctuations in concentrations and flow. The following are major disadvantages of activated carbon: (1) it is intolerant of high suspended solids levels, (2) it requires pretreatment for oil and grease removal when concentrations are greater than 10 ppm; (3) it is unsuitable for removing low molecular weight organics and highly soluble or highly ionized organics; (4) it is limited in practice to wastes with less than 10,000 ppm organics; and (5) it has high operation and maintenance costs.

Costs of tertiary granular activated carbon absorption are estimated in Table 11. The construction costs include vessels, media, pumps, carbon storage tanks, controls, and an operations building. The loading rate is 30 lb/Mgal; contact time is 30 minutes. Disposal costs of spent carbon are not included. Operation and maintenance costs include pumping, labor, and maintenance. No regeneration is included.

Chemical Oxidation (Chlorination)

Chlorine is widely used in wastewater treatment for disinfection, odor control, and BOD reduction. It combines with water to form hypochlorous acid which, in turn, can ionize to the hypochlorite ion.

$$Cl_2 + H_2O \longrightarrow HCl + HOCl \underset{pH\ 7}{\overset{pH\ 8}{\rightleftharpoons}} H^+ + (OCl)^- \qquad \text{[Eq 3]}$$

[32]R. L. Culp, et al.

Table 10

Typical Operating Parameters for Carbon Adsorption Equipment
(Adapted from B. G. Liptak, ed., Environmental Engineer's Handbook, Vol I: Water Pollution [Chilton Book C., 1974]; R. L. Culp et al., Handbook of Advanced Wastewater Treatment [Van Nostrand Reinhold Co., 1978]; D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes [Noyes Data Corp., 1978]; Innovative and Alternative Technology Assessment Manual, EPA-430/9-78/009 [U.S. Environmental Protection Agency, 1978].)

Parameter	Requirements*
Contact time	Generally 10 to 50 minutes; may be as high as 2 hours for some industrial wastes
Hydraulic load	2 to 15 gpm/sq ft of bed area depending on type of contact system
Backwash rate	Rates of 20 to 30 gpm/sq ft usually produce 25 to 50 percent bed expansion
Carbon loss during regeneration	4 to 9 percent 2 to 10 percent
Material removed per unit weight of carbon (wt/wt)	0.2 to 0.8
Carbon requirements:	
Primary plant	500 to 1800 $lb/10^6$ gal
Tertiary plant	200 to 500 $lb/10^6$ gal
Bed depth	10 to 30 ft

Table 11

Estimated Cost for Tertiary Activated Carbon Leachate Treatment

Flow, mgd	Construction Cost, $K	Operation and Maintenance Cost, $K
0.1	80	26
0.3	170	52
0.6	280	85
1.0	400	120

The disinfection potential is related to the strong oxidizing properties of hypochlorous acid (HOCl) and to a lesser extent, the hypochlorite ion (OCl). The effectiveness of wastewater chlorination depends on pH, temperature, time of contact, degree of mixing, and presence of interfering substances.[33] The extent to which hypochlorous acid ionizes to form the weak oxidizing hypochlorite ion depends on pH and temperature. At values more basic than pH 7.5, the less effective hypochlorite ion is the prevalent species in aqueous solutions. Since hypochlorous acid is a more powerful oxidant, a pH of less than 7.5 should be maintained. The rate of bacterial kill increases with the time of exposure to chlorine. A detention time of 15 to 30 minutes is generally required in a baffled, closed tank system.[34] Complete and uniform mixing of chlorine with wastewater is important to disinfection. Any shortcuts will decrease the process' efficiency; therefore, tank shape mixing and proper baffling are critical.[35] Rapid initial mixing may be important; the residuals formed first are apparently more bactericidal than compounds formed later.

Chlorine reacts readily with ammonia in water to form chloramines, which are much less effective oxidizing agents. Chlorine also oxidizes ferrous iron, sulfides, and nitrates. The presence of these species increases the chlorine demand (i.e., the amount of chlorine that will combine with various

---

[33] B. G. Liptak.
[34] B. G. Liptak.
[35] R. L. Culp et al.

chemicals before it begins to appear as free chlorine residual) and increases the required dosage.[36]

The size of the chlorinator is based on the water's chlorine demand and flow rate. Typical chlorine dosages for disinfection are 3 to 15 mg/L for trickling filter effluent and 2 to 8 mg/L for activated sludge effluent.[37] The chlorinator is equipped with a feed control system; the simplest and least expensive is a manual device. Automatic ratio control devices are available that can adjust the chlorine dosage to changes in flow rate. A more sophisticated system can include a residual chlorine analyzer, which controls the chlorine dosage based on residual chlorine levels.[38]

The most common chlorine compounds used in wastewater treatment are chlorine gas, and calcium and sodium hypochlorite. The latter two are used in small treatment plants where simplicity and safety are more important than cost. Because calcium hypochlorite granules are readily soluble in water and are relatively stable when stored properly, they are often favored.[39] Chlorine gas is dangerous to store and use.

Chemical oxidation by chlorination has the following advantages: (1) it markedly reduces concentrations of harmful organisms, (2) the process is very reliable, and (3) it is less expensive than other methods of disinfection and oxidation, such as use of ozone. The process has the following disadvantages: (1) it may cause formation of chlorinated hydrocarbons, (2) chlorine gas is hazardous and requires careful handling, and (3) chlorine reacts with many chemicals in water, so the system must be adjusted to the leachate's strength. For selected flowrates, Table 12 gives the expenses of chlorination needed to oxidize and disinfect. The costs include chlorine supply, chlorinator, and contact chamber. These figures are based on a 15-year service life, 10 mg/L dosage, and a contact time of 30 minutes.

Flow Equalization

The primary objective of flow equalization basins is to lessen the effects of peak leachate flow and high leachate concentrations. Both biological and physical/chemical processes operate more effectively if the composition and volume of the influent are fairly constant. Because leachate's flow and strength vary considerably, equalization basins almost always will be needed to increase the stability of biological and physical/chemical unit operations.

In computing equalization volume requirements for leachate treatment systems, the water balance equation must be used to determine flow and to design for annual peak rainfall or near peak flow volume of the area. In sizing the equalization basin, the designer first needs to determine the amount of fluctuation that the other unit operations in the treatment process can handle without impairing performance. Then equalization volumes should be provided to ensure that fluctuation does not exceed that amount. Basins can be

---

[36]B. G. Liptak.
[37]Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment and Disposal (McGraw-Hill Book Co., 1979).
[38]B. G. Liptak.
[39]Metcalf and Eddy, Inc.

Table 12

Estimated Costs for Chlorinating Effluent From Leachate Treatment Plants

Flow, mgd	Construction Cost, $	Operation and Maintenance Cost, $
0.1	22,000	4,500
0.3	32,000	7,200
0.6	40,000	10,000
1.0	50,000	12,000

designed for either side-line equalization, where water exceeding the daily flow is equalized, or for in-line equalization, where the entire daily flow is equalized. Because of large fluctuations in the concentrations of pollutants, leachate treatment usually requires inline equalization.

The following factors must be considered when an equalization basin is designed: (1) the degree of flow rate and organic loading equalization required to ensure reliable and efficient performance of other process units, (2) the aeration and mixing equipment needed, (3) the pumping and discharge flow rate control specifications, and (4) the size of alternative treatment components for peak flows. Aeration and mixing equipment needs to be selected carefully. As a guideline, the minimum mixing required to prevent deposition of solids in municipal treatment systems (at 200 mg of suspended solids) ranges from about 0.02 to 0.04 hp/1000 gal. Minimum aeration required to prevent septic conditions is about 1.25 to 2.0 cfm/1000 gal.

Equalization basins are generally reliable and can be easily designed. They can dramatically increase the stability of leachate flow or concentration for sensitive operations such as carbon adsorption, biological treatment, precipitation, and ion exchange. The only advantage is that an equalization basin may require a considerable amount of land to handle peak flows.

The costs for concrete basins with a detention time of 1 day range from $70,000 to $150,000 for construction (0.1 to 1.0 mgd). Operation and maintenance costs are usually quite low and run from $2500 to $10,000 per year for the same range of flows.

Ion Exchange [illegible]

Ion exchange resins are insoluble solids. They contain fixed cations and anions capable of reversible exchange with mobile ions of the opposite sign in solutions which the resins contact. The direction and extent of the reaction are governed by the relative insolubilities of the salts that can be formed and the equilibrium constants.[40] Ion exchange can remove the following classes of chemicals: (1) all soluble metallic elements, either cationic or anionic; (2) anions such as halides, cyanides, and nitrates, and (3) acids such as carboxylics, sulfonics, and some phenols at a pH sufficiently alkaline to give the ions.

However, certain limitations on the ion exchange capability of various resins must be considered to decide whether ion exchange and its pretreatment requirements are feasible. For efficient operations, the upper concentration limit for exchangeable ions is about 2500 mg/L expressed as calcium carbonate, or 0.05 equivalents/L. This is the upper limit primarily because high concentrations of exchangeable ions rapidly exhaust the resin during the process, and costs for regeneration become prohibitively high. Also, the effectiveness of ion exchange resins can be decreased by the presence of certain waste constituents. There must be little suspended matter so the resins do not foul. Oxidizing agents such as chromic or nitric acid also can damage resins. Finally, some organics, especially aromatics, can be irreversibly adsorbed by the resin, resulting in decreased capacity.[41] This problem sometimes can be solved by prefiltering the wastewater or by using scavenger exchange resins.[42]

Ion exchange is now being used in several industrial treatment processes, which suggests that it may be suited for treating some hazardous waste leachates. Notably, ion exchange is widely used in the electroplating industry to remove impurities from rinse waters. Usually, these are fairly dilute solutions of chromium, nickel, and cyanides. Ion exchange is generally used as a polishing step in the treatment of electroplating wastes and is also widely used as a final treatment method for metal finishing wastewaters to remove cyanides, zinc, chromium, and other metals. Another application is for removing valuable metals such as copper, molybdenum, cobalt, and nickel from the dilute leach liquors of tailing or dump piles.[43]

The major design considerations for ion exchange treatment include selection of the appropriate resin (based on organic loads), determination of hydraulic load, selection of the appropriate operating mode, and determination of backwashing and regeneration requirements. The extent to which anions or cations are removed depends on the equilibrium established between the ions in the aqueous phase and those in the solid phase. For instance, the equilibrium for the removal of sodium from solution is defined as follows:

---

[40] D. H. De Renzo.

[41] D. H. De Renzo.

[42] Metcalf and Eddy, Inc.

[43] N. L. Nemerow, Industrial Water Pollution: Origin, Characteristics and Treatment (Addison-Wesley Publ. Co., 1978); D. H. De Renzo.

$$\frac{[H] \times RNa}{[Na] \times RH} = K_s \qquad [Eq\ 4]$$

where: K_s = selectivity coefficient
RH = mole fraction of hydrogen on the exchange resin
RNa = mole fraction of sodium on exchange resin
[ ] = concentration in the solution phase.

The selectivity coefficient depends on the nature and volume of the ion, the type of resin and its saturation, and the ion concentration in the wastewater.[44] Since the stability of the salts formed by the ions and exchangers can be highly variable, it is important to choose the exchange material carefully to allow selective separation. Exchange resins can be selected and compared by the following criteria: (1) functionality, which refers to the kinds of ions that are exchanged, (2) exchange capacity, which is a measure of the total uptake of specific ions, and (3) selectivity, which refers to the preference of one kind of exchangeable ion over another.[45] Table 13 lists some available resin types and reactive groups that may be well suited to leachate treatment.

Continued contact of the exchange resin with the solution containing the ions to be removed eventually exhausts the active sites on the resins. Before this happens, the resins usually should be regenerated. Table 14 summarizes the types of regenerants and dosage ranges. Optimum regenerant quantities and conditions vary with the process involved and must be determined experimentally.

Advantages of ion exchange resins include the following: (1) the process is suitable for removal of soluble inorganics most often not removed by precipitation/sedimentation; (2) the technology has been reasonably well demonstrated for electroplating wastes, metal, and pickling liquors; and (3) the process has low energy requirements. There are four disadvantages: (1) the process is not suitable for removing high concentrations of contaminants; (2) pretreatment is required for suspended solids, certain organics (especially aromatic), and oxidants; (3) operation and maintenance costs are high compared with those of most treatment processes; and (4) spent regenerant can contain high concentrations of contaminants.

Costs of ion exchange vary widely, depending on stream size, and type and concentration of contaminants. Treatment costs have been estimated to be about $6/1000 gal for dilute, complex waste streams.[46]

Liquid Ion Exchange

Liquid ion exchange (LIE) involves the selective removal or separation of free and complexed metal ions and other inorganics from aqueous streams. In this process, the inorganics of interest are transferred from the aqueous phase to an immiscible organic phase. This organic phase is then contacted with a second aqueous phase whose composition is such that the inorganics now transfer to that phase. The basic principle underlying the LIE reaction is

---

[44] Metcalf and Eddy, Inc.
[45] D. H. De Renzo.
[46] D. H. De Renzo.

Table 13

Common Reactive Groups for Ion Exchange Resin
(Adapted from D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes [Park Ridge, NJ: Noyes Date Corporation, 1978].)

Reactive Group	Exchangeable Ions
Strong acid (sulfonic)	Cations in general
Weak acid (carboxylic)	Cations in general
Weak acid (phenolic)	Cesium and polyvalent cations
Strong base (quaternary amine)	All anions, especially suited for anions of weak acids (cyanide, carbonate, silicate, etc.)
Weak base (tertiary and secondary amine)	Anions of strong acids (sulfate, chloride, etc.)
Chelating (varied, may be imino-diacetate or oximine groups)	Cations, especially transition and heavy elements

Note: Differences in the particular starting materials and preparation route frequently cause differences in handling properties, stability, and reaction kinetics between resins that have the same polymer backbone, functional groups, and exchange capacity. Hence it is important to test a variety of resisn for a particular application.

Table 14

Examples of Regenerants and Dosage Ranges for Different Types of Exchange Resins

Resin Type	Desired Ionic Form	Regenerant	lb/cu ft	Concentration Percent
Cationic	H^+	HCl	4 to 10	1 to 10
	H^+	H_2SO_4	6 to 12	2 to 10
	Na^+	NaCl	5 to 10	6 to 25
Strong basic anionic	OH^-	NaOH	4 to 8	2 to 10
Weak basic anionic	NH_4^-	Free base	1 to 2	2 to 4
	NaOH	Free base	2 to 4	1 to 2

the distribution or partition between phases. In the LIE process, a water-soluble, ionic species is caused to become more soluble in an organic solvent (by salt formation or complexation, for example). This promotes the partition or extraction of the species into the solvent.[47]

LIE is competitive with conventional ion exchange and can be used to treat much higher concentrations that the conventional process. LIE is applicable to any aqueous waste stream containing extractable species and to any wastes containing inorganics that can be dissolved in aqueous acid or alkali to yield extractable species. Virtually all soluble cations can be removed, although commercially available extractants preferentially extract heavy polyvalent metals. Soluble but undissociated species -- such as mercuric chloride, anions, and metal oxyanions -- and weak acids, such as hydrofluoric acid, can also be extracted.[48] The process is sensitive to certain wastewater contaminants: the presence of surfactants causes changes in phase separation; oxidants tend to cause degradation of functional groups of extractants; and the presence of suspended matter over 0.1 percent may hinder the process.

Although in theory there is no limit to the concentrations that can be treated by this process, the volume of extractants that must be used places practical limitations on the concentrations. Commercial processes for extraction of cobalt and nickel treat solutions up to 10 g/L, and this is probably a typical upper limit.[49] There are several commercial and near-commercial applications for removal of various inorganics by LIE. Some examples include: (1) recovery of nitric, hydrofluoric, and molybdic acid from metal pickling liquors; (2) recovery of copper from spent alkaline etchant solutions and from ammonia/ammonium carbonate leaching of metallic copper scrap; (3) recovery of iron, zinc, copper, nickel, and chromium from alkali hydroxide sludges; and (4) removal of cyanide and zinc from electroplating rinse water.[50]

Liquid ion exchange is a steadystate process because of its dependence on a constant distribution coefficient and on proper time for phase separation. The contacting process should provide thorough mixing to allow as much mass transfer as possible. Therefore, the process should be run continuously rather than as a batch operation.

Extraction reagents are classified according to differences in the nature of stripping chemistry. The reagents are used as dilute solutions (5 to 30 percent). Classes of reactants include: (1) basic extractants -- such as ketones, ethers, and amines -- which react with acids or metallic ions to form salts or complexes soluble in organic solvents; (2) acidic extractants -- such as carboxylic acids, and napthalenes and alkylaphalene sulfonic acids -- which react with bases or salts by exchange of cations; (3) chelating extractants which form stable chelate complexes with metal ions; and (4) ionic extractants, which form organic extractable ion pairs with anions or cations.[51]

The process yields two aqueous streams: the cleaned stream and the stripping liquor. Both contain small amounts of the extraction solvent. The

---

[47]D. H. De Renzo.
[48]D. H. De Renzo.
[49]D. H. De Renzo.
[50]D. H. De Renzo.
[51]D. H. De Renzo.

"cleaned" aqueous stream may require further treatment by adsorption before stream discharge. The stripping liquor contains high concentrations of hazardous wastes which must be treated.[52]

Liquid ion exchange has advantages in that (1) it can treat most dissolved ionized and un-ionized inorganics in aqueous streams; (2) the process has been proven reliable in treating pickling liquor and electroplating wastes; and (3) the process can treat higher inorganic concentrations than can conventional ion exchange. Major disadvantages include the following: (1) the process is sensitive to the presence of oxidants, surfactants, and suspended solids; (2) water pollution is possible unless reclaimed extractants are stripped from the discharge stream; and (3) the regeneration solution into which hazardous components are stripped from the extraction solvent contains high concentrations of hazardous components which must be made harmless. Few economic studies have been done on the treatment of dilute waste streams. Costs appear to be comparable to or somewhat less than conventional ion exchange.

Precipitation, Flocculation, and Sedimentation

Precipitation, flocculation, and sedimentation are well-developed processes that have been applied to the treatment of various industrial wastewaters containing particulates or soluble heavy metals. Precipitation removes a substance from solution and transforms it into a solid particle. Flocculation promotes particle growth of suspended solids so that they can be more easily removed, and sedimentation removes suspended particles from the liquid by settling.

Precipitation, flocculation, and sedimentation are suitable treatment methods whenever precipitable soluble substances or suspended solids must be removed. Many toxic metals, including cadmium, lead, arsenic, and chromium, are successfully removed from wastewater precipitation, flocculation, and sedimentation. There is no upper limit on the concentrations that can be treated by these processes. The lower limit for removal of soluble species generally depends on the solubility product of the particular ion, although this method of predicting removal efficiency is not very reliable.

The major features to consider in the design of a sedimentation basin or clarifier are the hydraulic flow, chemical requirements, and dosages. These factors depend on the concentrations of suspended matter and precipitable soluble species, and on the settling rate. The three processes can be carried out in separate basins, or a clarifier may be used with separate zones for chemical mixing, precipitation, flocculation, and sedimentation. When the three processes are applied, laboratory tests can be used to determine the degree of precipitation, reaction time, and required chemical dosage; the type of flocculant; and the settling rate.

<u>Precipitation</u>. Two precipitation reactions usually are applied to leachate treatment. The first is adding a compound, such as sulfide, that will react directly with the hazardous metal to form a sparingly soluble compound. The second is changing the equilibrium, especially by pH adjustment with lime [$C_a(OH)_2$] so that a soluble compound becomes insoluble and

---

[52]D. H. De Renzo.

precipitates. Precipitation of metals is governed by the solubility product of the metal ion. However, when metals are precipitated the effluent concentrations usually are not equal to the theoretical solubility. Many metals form complexes with organo-metallics. These ions are, in some cases, more soluble than the ion itself and may prevent precipitation. Cyanide ions or other ions in the wastewater may complex with metals, making them difficult to precipitate as the hydroxide or sulfide.[53]

Lime precipitation is the most widely used method for precipitating heavy metals. However, there are problems with the process. Many metals reach a minimum solubility at a specific pH, but further addition of lime causes the metal to become soluble again (amphoteric metals). Therefore, the dosage needs to be accurately controlled. However, the fluctuating leachate quantities and concentrations of metals make it very difficult to control the lime dosage to obtain ideal precipitation; jar tests need to be conducted frequently. Lime dosage requirements for landfill leachate may be considerably higher than those for municipal wastewater treatment. Whereas municipal wastewater systems require dosages of about 250 to 400 mg/L to obtain a pH of 10.5 (depending on alkalinity of the water), the Geological Reclamation Operations and Waste Systems, Inc. (GROWS) landfill leachate treatment system in Bucks County, PA, requires about 6000 mg/L to obtain a pH of 10.[54] Also, some metals require very high pH for precipitation as the hydroxide; so the effluent must then be neutralized before it can meet discharge pH limitations or be at an acceptable pH for biological treatment.

Precipitation as the metal sulfide is an alternative that has not been used widely. As shown in Table 15, metal sulfides are less soluble than hydroxides, and generally the metal can be reduced to lower concentrations.

Coagulation/Flocculation. Settling of suspended solids depends on gravitational or inertial forces to remove solid particles. Coagulation and flocculation are intended to overcome repulsion forces of individual particles, causing them to agglomerate into larger particles. Chemicals used for coagulation and flocculation include alum, ferric chloride, ferric sulfide, lime (coagulants), and polyelectrolytes (flocculants). For a given application each coagulant has an optimum concentration and pH range. The processes of coagulation and flocculation require rapid mixing followed by a slow and gentle mixing to allow contact between small particles and agglomeration into larger particles. Coagulants must be completely dispersed into water immediately. This is especially true for inorganic coagulants, such as alum, that precipitate rapidly. For lime treatment, it is useful to disperse the lime throughout the wastewater in the presence of recycled sludge to provide an abundance of surface area on which the precipitate can form.[55] Rapid mix is usually accomplished in 10 to 60 seconds.

The required dosage of coagulant depends on pH, alkalinity, phosphate levels, and mode of mixing; dosage can be determined by jar tests and zeta potential tests. Typical chemical dosages used in industrial treatment processes are listed in Table 16. The hydraulic loading is used as a basis

---

[53] D. H. De Renzo.

[54] R. L. Steiner et al., Demonstration of a Leachate Treatment Plant, PB-269-502 (Office for Solid Wastes, U.S. Environmental Protection Agency, 1977).

[55] Hardam Azad.

Table 15

Approximate Solubilities of Selected Metals in Water
(Date in g/L)*

Metal	Solubility as Hydroxide	Solubility as Sulfide	Factor**
Iron	9×10^{-1}	3×10^{-5}	3×10^{4}
Zinc	1×10^{0}	2×10^{-7}	5×10^{6}
Cadmium	2×10^{-5}	7×10^{-10}	3×10^{4}
Nickel	7×10^{-3}	7×10^{-1}	1×10^{5}
Copper	2×10^{-2}	6×10^{-13}	3×10^{15}
Lead	2×10^{0}	4×10^{-5}	5×10^{4}
Mercury	4×10^{-4}	9×10^{-20}	4×10^{15}
Silver	1×10^{-1}	7×10^{-12}	1×10^{12}
Chromium	8×1^{-4}	(No precip.)	

*From Sulfex Heavy Metals Waste Treatment Process, Technical Bulletin 13: 6 (Permutit, Inc., 1977).

**Factor $= \frac{\text{Solubility as hydroxide}}{\text{Solubility as sulfide}}$.

Table 16

Chemical Treatment of Industrial Wastewater by Coagulation
(From Hardam Azad, ed., Industrial Wastewater Management Handbook [New York, New York: McGraw-Hill, 1976].)

Criteria	$FeCl_3$	Alum	$Ca(OH)_2$
Dose, mg/L	80 to 120	100 to 150	350 to 500
Hydraulic loading, gpm/sq ft*	0.3 to 0.4	0.2 to 0.4	0.5 to 0.8
Chemical sludge production, lb/million gal	350 to 700	250 to 500	4000 to 7000

*Without use of polyelectrolytes.

for determining suspended solids removal efficiencies. The hydraulic loadings shown are intended to achieve 80 to 90 percent suspended solids removal.[56]

After achieving effective mix, promotion of particle growth by flocculation is the next step. Flocculants usually are added downstream from the coagulent addition point because the rapid mixing can break up the floc. Flocculation takes 15 to 30 minutes. Mean temporal velocity gradients of 40 to 80 ft/sec-ft are recommended. The lower value is for fragile floc (aluminum or iron), and the higher value is for lime.[57]

Sedimentation. As indicated previously, sedimentation may be done in a separate basin from precipitation and coagulation, or all three processes may be carried out in the same basin. When the operations are carried out in combination, two design configurations are available. In the conventional system, rapid mix is completed "inline" before water enters the large settler where flocculation and clarification are completed. In the sludge-blanket units, coagulation mixing, flocculation, and settling all take place in a single unit.[58]

The criteria for sizing settling basins are overflow rate (surface settling rate), tank depth at the side walls, and detention time. For municipal treatment systems, depths average 10 to 12 ft; detention time usually averages 1 to 3 hours; and surface loading rates average 360 to 600 gal/day/sq ft for alum floc, 540 to 1200 gal/day/sq ft for lime floc, and 700 to 800 gal/day/sq ft for $FeCl_3$.[59]

Package plants suitable for coagulation, flocculation, sedimentation, and filtration are available for small flows (10,000 gpd to 2 mgd). These plants, which are available either as factory-preassembled units or field-assembled modules, significantly reduce the cost of small facilities. The units are automatically controlled and require only minimal operator attention. Cost estimates are detailed in Tables 17 and 18. These estimates were developed for standard manufacturer units incorporating 20 minutes of flocculation, tube settlers rated at 150 gpd/sq ft, mixed filters rated at 2 and 5 gpm/sq ft, and a media depth of 30 in. The costs include premanufactured treatment plant components, mixed media, chemical feed facilities (storage tanks and feed pumps), flow measurement and control devices, pneumatic air supply for valve and instrument operation (applies to plants of 200 gpm and larger), effluent and backwash pumps, all necessary controls for a complete and operable unit, and building. The three smallest plants have low-head filter effluent transfer pumps and are to be used with an above-grade clearwell. The larger plants gravity discharge to a below-grade clearwell. Raw water intake and pumping facilities, clearwell storage, high-service pumping, and site work, exclusive of foundation preparations, are not included in the costs. Complete treatment package plants (coagulation, flocculation, sedimentation, and

[56]Hardam Azad.

[57]Azad.

[58]B. G. Liptak.

[59]Innovative and Alternative Technology Assessment Manual, EPA-430/9-78-009 (U.S. Environmental Protection Agency, Office of Water Program Operations, 1978).

Table 17

Construction Cost for Package Complete Treatment Plants Used for Precipitation, Flocculation, Sedimentation, and Filtration (From R. L. Culp et al., Handbook of Advanced Wastewater Treatment, [Van Nostrand Reinhold Co., 1978].)

	Plant Capacity, gpm*							
Cost Category	4 and 10	8 and 20	40 and 100	80 and 200	140 and 350	225 and 560	280 and 700	560 and 1400
Excavation and site work	$ 210	$ 270	$ 390	$ 550	$ 810	$ 340	$ 1310	$ 2210
Manufactured equipment	13,050	16,340	30,770	53,040	72,140	89,110	106,090	185,650
Concrete	370	460	690	1100	1950	2070	3110	4590
Labor	5360	6310	7360	10,720	14,290	17,660	25,230	39,410
Pipe and valves	1060	1710	1590	3980	3610	4360	5950	9250
Electrical and instrumentation	16,360	17,570	21,580	21,580	26,990	30,140	49,100	67,210
Housing	15,960	17,460	21,740	29,240	48,840	51,080	73,150	103,880
Subtotal	52,370	59,580	84,120	119,210	168,630	195,260	263,940	412,200
Miscellaneous	7860	8940	12,620	17,880	25,290	29,290	39,590	61,830
Total	60,230	68,520	96,740	137,090	193,920	224,550	303,530	474,030

*Lower capacity represents a filtration rate of 2 gpm/sq ft; higher capacity represents a filtration rate of 5 gpm/sq ft.

Table 18

Operation and Maintenance Summary for Package Complete Treatment Plants Used for Precipitation, Flocculation, Sedimentation and Filtration
(From R. L. Culp et al., Handbook of Advanced Wastewater Treatment [Van Nostrand Reinhold Co., 1978].)

Plant Capacity, gpm	Energy, kWh/yr			Maintenance Material, $/year	Labor, hr/year	Total Cost,* $/year
	Building	Process	Total			
Filtration rate of 2 gpm/sq ft						
4	$ 30,780	$ 320	$ 31,100	$ 320	$1460	$15,830
8	38,730	390	39,170	590	1460	16,360
40	61,560	3210	64,770	860	1750	20,300
80	98,300	3950	102,450	1600	3200	36,670
140	174,420	6920	181,340	1920	3600	43,360
225	184,680	11,060	195,740	2140	3600	44,010
280	277,020	13,830	290,850	2570	3600	47,300
560	410,400	27,660	438,060	3210	5400	70,350
Filtration rate of 5 gpm/sq ft						
10	30,780	780	31,360	320	1460	15,370
20	38,780	1360	40,340	590	1460	16,400
100	61,560	7810	69,370	860	1750	20,440
200	98,500	9470	107,970	1600	3200	36,340
350	174,420	16,580	191,000	1920	3600	43,650
360	184,680	26,520	211,200	2140	3600	44,480
700	277,020	33.150	310,170	2570	3600	47,880
1400	410,400	66,300	476,700	3210	5400	71,510

*Calculated using $0.03/kWh and $10.00/hr of labor.

filtration) are designed for essentially unattended operation -- that is, they backwash automatically on the basis of head loss or excessive filtered water turbidity, and then return to service.[60]

Reverse Osmosis

In reverse osmosis, water is separated from dissolved salts and organic materials by filtering through a semipermeable membrane at a pressure above the osmotic pressure of the water caused by the dissolved materials. With existing membranes and equipment, operating pressures up to 1000 psi are common. The basic components of the reverse osmosis unit are the membrane, a membrane support structure, a containing vessel, and a high-pressure pump. Cellulose acetate and nylon are commonly used as membrane materials. There are four types of membrane support configurations: spiral-wound, tubular, multiple-plant, and hollow-fiber. The tubular design is recommended for use with wastewaters.[61] Units can be arranged in parallel to increase the hydraulic capacity, or in series to affect the degree of demineralization required.

A high-quality feed is required for efficient operation of a reverse osmosis unit. A secondary effluent usually must be pretreated with filtration and carbon adsorption. The removal of iron and manganese may also be necessary.[62] Preliminary experiments using reverse osmosis on high-strength leachates were not successful because of the rapid fouling of the membrane system with suspended solids and precipitated iron hydroxide, and the poor selectivity for small organics.[63] Except for possible use as a final polishing step, reverse osmosis using current technology on raw landfill leachates was found to be impractical.

Advantages of reverse osmosis include the capability to separate organic and inorganic material from water. Major disadvantages are its high cost, the experimental nature of the technology, and the large residual of semiconcentrated liquid effluent.

Costs of reverse osmosis are very high now. Average costs of \$1.67/gal/day and \$3.33/gal/day were estimated for 30,000- and 3000-gpd treatment plants.[64] Power requirements were 20 hp for the larger plant and 2 hp for the smaller. These costs include pretreatment by slow sand filtration, activated carbon adsorption, and filtration through an 0.5-micron filter.

Wet Air Oxidation

Wet air oxidation is based on the concept that any substance capable of burning can be oxidized in the presence of air at elevated pressure and moderate temperature. Wastewater containing some oxidizable material is mixed with air and pumped through an exchanger. It is then pumped to a reactor,

---

[60] Estimated Waste Treatment Costs, Vol 3: Cost Curves Applicable to 2500 gpd to 1.0 mgd Treatment Plants, EPA-600/2-79-162c (U.S. Environmental Protection Agency, 1979).
[61] Metcalf and Eddy, Inc.
[62] Metcalf and Eddy, Inc.
[63] E. S. K. Chian and F. B. DeWalle, Vol II.
[64] E. S. K. Chian and F. B. DeWalle, Vol II.

where oxygen in the air reacts with organic matter in the wastes. Oxidation is accompanied by a rise in temperature, and the heat produced can be used to sustain the process. After the reaction phase, gas and liquid are separated, and the liquid is used to heat the incoming material.[65]

Wet air oxidation may be applied to a wide class of wastewaters, such as those from the manufacture of pesticides, petrochemicals, pharmaceuticals, or other industrial chemicals.[66] The process generally treats wastes with a high COD, ranging from 5 to 150 g/L, and, in general, is only suitable for high strength wastes. The performance of wet air oxidation has been well demonstrated for the treatment of acrylonitrile wastes with high concentrations of cyanide and for the treatment of scrubbing liquor from the clean-up of coke oven gas, which contains cyanides, thiocyanates, and thiosulfates. These wastes are now treated on an industrial scale. The process also has been shown to oxidize effectively a number of toxic organics on a bench-scale level. Wet air oxidation takes place by a family of related oxidation and hydrolysis reactions. These reactions lead to partially oxidized intermediate products and, if reactor residence time and temperature permit, eventually to carbon dioxide and water. Hence, the degree of oxidation is primarily a function of reaction temperature and residence time.[67]

Advantages of wet air oxidation are: (1) the process can handle high waste concentrations of 5 to 150 g/L; (2) the reactor can be thermally self-sustaining at COD concentrations of 15 000 ppm, thus reducing operating costs; and (3) the process creates no air pollution problems. Disadvantages include the following: (1) stainless steel equipment leads to higher capital costs than for incineration; (2) an additional heat source will be needed when the organic load is less than 15,000 ppm COD; and (3) the process requires well-trained operators.

The costs of wet air oxidation are proportional to the volume of the waste stream, the required pressure, and the amount of air and auxiliary steam required. No cost estimates are available now for the wet air oxidation process.

Biological Unit Processes

The major objectives of biological treatment of sanitary landfill leachate are to reduce the dissolved organic content, to remove heavy metals and nutrients such as nitrogen and phosphorus, and to coagulate and remove colloidal solids. The major treatment effects are caused by incorporation of these materials into microorganisms' tissues. The microorganisms can either be attached to media (trickling filters, rotating biological contactors, or anaerobic filters), or settled out and discarded (lagoons and stabilization ponds), or recycled (activated sludge systems). The biological unit processes discussed in this report are listed in Table 19. The rest of this chapter addresses general design criteria, advantages and disadvantages, and costs of the various biological processes.

---

[65] *Handbook for Remedial Action at Waste Disposal Sites.*

[66] *Industrial Pollution Control Systems* (Zimpro Environmental Control Systems, Inc., 1979).

[67] *Industrial Pollution Control Systems.*

Table 19

Summary of Biological Leachate Treatment Processes
(Adapted from B. G. Liptak, ed., Environmental Engineer's Handbook, Vol I: Water Pollution [Chilton Book Co., 1974]; Environmental Protection Agency, 1979; D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes [Noyes Data Corp., 1978]; M. J. Hammer, Water and Wastewater Technology [John Wiley & Sons, 1975].)

Treatment Method	Feed Stream Requirements and Limitations	Major Design and Performance Criteria	Environmental Impact	Technology Status	Reliability
Activated sludge	Can handle BODs of 10,000 ppm Requires low level of suspended solids--usually 1 percent Oil and grease should be less than 50 mg/L Effective for readily degradable organics or organics to which it can be acclimated Sensitive to heavy metals	Detention time Organic load Food to microorganism ratio Aeration	Generate excess sludge containing refractory organics and metals that have been sorbed	Highly developed; widely used	Process reliability is very good in absence of shock loads
Aerobic, anaerobic, aerated, or facultative lagoons	Requires very low suspended solids (0.1 percent) Requires low strength organic wastes (except) anaerobic) Sensitive to heavy metals and oil and grease	Detention time Depth Organic load pH Oxygen levels	May create odors; may release volatiles, H_2S, and methane if anaerobic; must be lined to prevent seepage into groundwater	Well demonstrated for stabilization of organics but not widely used	High if proper pH maintained and organic load is low; sensitive to shock loads since no sludge recycled
Land application	Sensitive to phytotoxic and precipitated materi- such as iron and manganese	Application rate Soil type Climate Vegetative types Application system Soil water/surface water monitoring	May create major odor problem if design application rates are exceeded. Heavy metals may accumulate in soil	Demonstrated but not widely employed	High, if low strength aerated leachate is used
Leachate recycling	Can handle large amounts of high strength leachate	Application rate Evapotranspiration Application system	Accelerates gas production with fire-explosion hazard. Possible odor problems. Can accumulate salts and metals	Demonstrated on pilot scale	Process reliability not proven

Table 19 (Cont'd).

Treatment Method	Feed Stream Requirements and Limitations	Major Design and Performance Criteria	Environmental Impact	Technology Status	Reliability
Pure oxygen-activated sludge	Requires suspended solid levels of about 1 percent or less	Detention time Organic load	Generates sludge containing refractory organics and sorbed metals	Relatively new technology but demonstrated for some industrial wastewaters	Reliability not fully established; complex and requires high level of maintenance
	Can handle higher organic loads than conventional activated sludge and is more tolerant of shock loads	Food-to-microorganism ratio Oxygen requirements			
	Sensitive to heavy metals and oil and grease				
Rotating biological contactor	Suitable for treatment of readily degradable organics; can handle higher organic loads than trickling filter but lower than activated sludge	Detention time Hydraulic load Organic load Temperature	Generates sludge containing refractory organics and sorbed metals; may cause odors	Process is relatively new, not widely used but gaining in popularity	Moderate in the absence of high organic loads and temperatures below 55°F
	Better suited to treatment of suspended or colloidal organics rather than soluble	Number of stages and trains			
	As with other biological processes, sensitive to oil and grease and metals				
Trickling filter	Can handle only very low organic loads as compared to activated sludge	Media type Hydraulic load Organic load	Generates sludge that contains refractory organics and sorbed metals; causes odors	Widely used as a roughing filter for industrial wastes	Fair for secondary treatment; moderate as a roughing filter
	Better suited to treating suspended and colloidal organics rather than soluble ones	Bed depth Temperature			
	As with other biological processes, sensitive to metals and oil and grease	Recirculation			

Most organic chemicals are biodegradable, although the relative ease of biodegradation varies widely. With properly acclimated microbial populations, adequate detention time, and equalization to ensure uniform flow, biological treatment can be used to treat many organics. There is considerable flexibility in biological treatment because there are several available processes, and microorganisms are remarkably flexible. Several generalizations can be made about the biological treatment of organics: (1) nonaromatics (noncyclic) hydrocarbons are preferable to aromatics; (2) materials with unsaturated bonds, such as alkenes, are preferred over materials with saturated bonds; and (3) stereochemistry affects the susceptibility of certain compounds to attack. Soluble organics are usually more readily degraded than insoluble materials; biological treatment is more efficient in removing dissolved or colloidal materials, which are more readily attacked by enzymes. The presence of key functional groups at certain locations can affect the degradation of compounds; alcohols, for example, are more easily degraded than their alkane or alkene homologues. On the other hand, addition of a Cl group or an NO_2 group increases resistance to biodegradation.[68]

Although many compounds in landfill leachate may be resistant at first to biological treatment, microorganisms can be acclimated to degrade many of these. Similarly, while heavy metals hinder biological treatment, the biomass can also be adjusted, within limits, to tolerate higher concentrations of metals. Table 20 lists concentrations of metals above which the treatment efficiency of aerobic sludge processes may lessen.

Activated Sludge

Activated sludge biological treatment of liquid waste is widely used in the sewage treatment industry and includes a broad range of treatment schemes which use completely mixed, aerobic reactors with sludge recycle. Activated sludge is a heterogenous microbial culture composed largely of bacteria, protozoa, rotifers, and fungi. The bacteria are responsible primarily for assimilating most of the organic material from the waste; the protozoa and rotifers complete the process by removing the dispersed bacteria that otherwise would escape in the plant effluent, giving high COD and suspended solids.[69] Aeration can be by air or by pure oxygen. Activated sludge systems are usually made up of several unit processes, including: primary sedimentation, an aerated reactor with sludge recycle, and clarification in a settling tank.

The air-activated sludge process has been proven effective in treating industrial wastewaters from refineries and coke plants, pharmaceutical wastes, polyvinyl chlorides (PVC) wastes, and food processing wastes.[70] Conventional activated sludge has successfully treated petroleum wastes with a BOD_5 as high as 10,000 ppm.[71] The process has also demonstrated that it can treat reasonably well the leachate from municipal landfills. For example, at the GROWS

---

[68]Selected Biodegradation Techniques for Treatment and Ultimate Disposal of Organic Materials, EPA-600/2-79-006 (U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, 1979).

[69]L. D. Benefield and C. W. Randall, Biological Process Design for Wastewater Treatment (Prentice-Hall, Inc., 1980), 526 pp.

[70]Estimated Waste Treatment Costs, Vol 3; Hardam Azad.

[71]Hardam Azad.

Table 20

Threshold Concentrations for Inhibitory Effects of Various Metals in Aerobic Activated Sludge Processes
(Adapted from D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes [Park Ridge, NJ: Noyes Data Corporation, 1978].)

Metal Ion	Inhibitory Threshold, mg/L
Cadmium	1 to 5
Chromium (+3)	10
Chromium (+6)	1 to 10
Copper	1 to 10
Iron (+3)	15
Lead	10
Nickel	1 to 2.5
Silver	0.03
Vanadium	10
Zinc	1 to 10

landfill, BOD removal of over 98 percent was achieved for an influent concentration of almost 5000 mg/L; the treatment system included physical/chemical as well as biological treatment.[72] Experiments have shown that activated sludge is generally well-suited to treatment of high strength leachates containing large concentrations of fatty acids. As the landfill stabilizes, the ratio of BOD/COD decreases, and the wastes become more resistant to biological treatment.[73]

The activated sludge process is sensitive to suspended solids, oil, and grease. It is recommended that suspended solids be less than 1 percent.[74] Oil and grease must be less than 75 mg/L, and preferably less than 50 mg/L, for effective treatment.[75]

Key design parameters for activated sludge include: (1) aeration period or detention time; (2) BOD loading per unit volume, usually expressed in terms of pounds of BOD applied per day per 1000 cu ft of aeratio basin; and (3) the

[72]Wastewater Treatment Facilities for Sewered Small Communities.
[73]Wastewater Treatment Facilities for Sewered Small Communities.
[74]D. H. De Renzo.
[75]Hardam Azad.

food-to-microorganism ratio (F/M), which expresses BOD loading with regard to microbial mass (usually measured as mixed liquor volatile suspended solids [MLVSS]). Several modifications of the activated sludge process may be applicable to treatment of hazardous leachate -- depending on the BOD loading and operational parameters for aeration processes.

Conventional treatment has limitations, such as a poor tolerance for shock loads, a tendency to produce bulking sludge that causes high suspended solids in the effluent, and low acceptable BOD loadings. But these problems can be partially solved by changes in process design. The completely mixed activated sludge process (Table 21) is the most widely used for treating wastewaters with relatively high organic loads. The advantages of this system are that it offers less variation in organic loading, resulting in more uniform oxygen demand and effluent quality; it dilutes the wastewater coming into the entire basin, resulting in reduced shock loads; and then it always uses the contents of the entire contactor because of complete mixing.[76]

The extended aeration process involves long detention times and a low F/M ratio. Process design at this low F/M ratio results in a high degree of oxidation and little excess sludge. The contact stabilization process, in which biological solids are contacted with the wastewater for a short time, then separated, and finally reaerated to degrade sorbed organics, has shown some success for industrial wastes with a high content of suspended and colloidal organics. Pure oxygen systems have overcome several major drawbacks of conventional treatment. These systems show increased bacterial activity, reduced aeration tank volume, and improved sludge settling.[77] The pure oxygen process is applicable to a wide range of wastes at high F/M ratios -- e.g., petrochemical, dye, pharmaceutical, and pesticide wastes.[78]

In addition to process modifications, there are several measures for minimizing upsets and maximizing stability. Problems with hydraulic and organic load variations can be limited by equalization preceding biological treatment. A method often used to provide more biodegradation is to increase the inventory of biological solids in the aeration basin. This is done by increasing the sludge-recycle ratio or reducing sludge wastage. However, such an approach usually requires trade-offs: higher sludge quantities lead to a greater need for food and air; also, old, heavy sludge tends to become mineralized and devoid of oxygen, creating a less active floc. The rate of return sludge may vary from 35 to 50 percent in systems carrying a low mixed liquor suspended solids (MLSS) concentration (≈2000 mg/L), and from 75 to 100 percent in systems carrying higher MLSS.[79] Suspended solids should be reduced as much as possible by sedimentation or filtration pretreatment. Since kinetics of biological degradation are concentration-dependent, dilution sometimes can minimize process upsets. Sludge bulking, which leads to poor effluent quality, can be controlled by pH adjustment, sufficient aeration, and adequate nutrient supply. An important consideration for leachate treatment is that microbial growth is a function of the limiting nutrient. Some leachates may

---

[76]Hardam Azad.
[77]Selected Biodegradation Techniques.
[78]Selected Biodegradation Techniques.
[79]Hardam Azad.

Table 21

Summary of Operating Parameters for Air-Activated Sludge and Pure Oxygen-Activated Sludge Treatment Systems

(Adapted from M. J. Hammer, Water and Wastewater Technology [John Wiley & Sons, 1975]; Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment, and Disposal [McGraw-Hill Book Co., 1979]; N. L. Nemerow, Industrial Water Pollution: Origins, Characteristics, and Treatment [Addison-Wesley Publ. Co., 1978].)

Process Modification	Aeration System	BOD Loading, $\frac{\text{lb BOD}_5}{\text{100 cu ft}}$	F/M Ratio, $\frac{\text{lb BOD/day}}{\text{lb MLVSS}}$	Mixed Liquor Suspended Solids (MLSS), mg/L	Applications and Limitations
Conventional (single aeration tank)	Diffused air, mechanical aerators	20 to 40	0.2 to 0.4	1500 to 3000	Low strength wastes; subject to shock load
Step aeration (multiple input point of waste in aeration tank)	Diffused air	40 to 60	0.2 to 0.4	2000 to 3500	Flexible and generally applicable to a wider range of wastes than conventional treatment. Uses lower volumes of air and shorter detention times than conventional process, but can handle higher BOD loads
Completely mixed	Diffused air, mechanical aerators	50 to 120	0.2 to 0.6	3000 to 6000	Resistant to shock loads, generally applicable
Extended aeration (low aeration rate)	Diffused air, mechanical aerators	10 to 25	0.05 to 2.0	3000 to 6000	Requires long detention times and low organic load, produces low volume of sludge; available as package plant

Table 21 (Cont'd)

Process Modification	Aeration System	BOD Loading, $\frac{\text{lb BOD}_5}{\text{100 cu ft}}$	F/M Ratio, $\frac{\text{lb BOD/day}}{\text{lb MLVSS}}$	Mixed Liquor Suspended Solids (MLSS), mg/L	Applications and Limitations
Contact stabilization (separate sludge aeration reactor)	Diffused air, mechanical	60 to 75	0.1 to 0.6	1000 to 2000* 4000 to 10 000**	Low aeration requirements; not suitable for soluble BOD
High rate	Mechanical aerators	80 up	0.5 to 1.0	4000 to 10 000	Well suited to shock loads; requires little supervision. However, requires long detention times, requiring three times as much air as conventional treatment
Pure-oxygen	Mechanical aerators	120 up	0.6 to 1.5	6000 to 8000	High efficiency possible at increased BOD loads and reduced aeration

*Contact unit.
**Solids stabilization unit.

be phosphorus- or nitrogen-limited. Requirements for nitrogen are 5 lb/100 lb BOD_5 removed, and for phosphorus, 1 lb/100 lb BOD_5 removed.[80]

Equipment used for activated sludge treatment varies considerably. Three major types of aerators are used: mechanical surface, diffuse air, and sparged turbine aerators. Mechanical surface aerators are considerably cheaper than diffused aerators; slow speed mechanical aerators are the cheapest means of oxygenation. Fine air diffusers or coarse air bubble diffusers usually provide compressed air diffusion in activated sludge reactors. The operator can increase or decrease oxygenation and mixing by changing the air-blower output. For variations greater than 50 percent, the number of diffusers should be changed. Sparged turbines are mechanically diffused air units. This form of diffused air is very fine and benefits from improved gas transfer kinetics. However, the sparged turbine generally does not transfer gas as efficiently as in the mechanical aerator.[81]

Secondary clarifiers are used to separate activated sludge solids from the mixed liquor and to produce the concentrated solids needed to sustain biological treatment. When multiple tanks are required, rectangular ones are preferable because they require less area than circular tanks. Average hydraulic loading varies from 400 to 800 gal/day/sq ft surface area, and peak loadings range from 700 to 1200 gal/day/sq ft, depending on MLSS concentration and percent sludge recycle. Average solids loading of 0.6 to 1.2 lb/hr/sq ft and peak loadings of 1.25 to 2.0 lb/hr/sq ft are typical for activated sludge plants. Depths are normally 12 to 15 ft.

Activated sludge processes have the following advantages: (1) activated sludge has been widely used in industrial wastewater treatment; (2) there are a number of process variations which allow for a high degree of flexibility; (3) process reliability is good (although not well known for pure oxygen-activated sludge); and (4) the processes can tolerate higher organic loads than most biological treatment systems. Some disadvantages are: (1) capital costs are high; (2) the process is sensitive to suspended solids and metals; (3) the process generates sludge which can be high in metals and refractory organics; it is subject to upsets from shock loads; and it is fairly energy intensive.

Costs of different types of activated sludge treatment vary widely depending on oxygen requirements, detention time, volumetric loadings, and F/M ratios. Table 22 gives cost estimates for three activated sludge systems and a final clarifier. Construction and maintenance costs are shown for a conventional treatment system with mechanical aeration and volumetric loadings of 32 lb BOD/day-1000 cu ft, MLSS of 2000 mg/L and 1.1 lb of oxygen supplied per pound of BOD removed, an F/M ratio of 0.25 lb BOD/day/lb MLSS, and a detention time of 6 hr.[82] Also included in Table 22 are construction and maintenance costs for extended aeration package plants (detention time of 24 hr) for flows down to 0.01 mgd. For this example, construction costs include comminutor, aeration basin, clarifier, chlorine contact chamber, aerobic digester, chlorine feed facility, building, and fencing. For the example of pure

[80]Hardam Azad; Metcalf and Eddy, Inc.; M. J. Hammer, Water and Wastewater Technology (John Wiley & Sons, 1975).
[81]Hardam Azad; Metcalf and Eddy, Inc.; M. J. Hammer.
[82]Innovative and Alternative Technology Assessment Manual.

Table 22

Estimated Construction and Operating and Maintenance Costs for Activated Sludge Treatment Systems

(Adapted from Innovative and Alternative Technology Assessment Manual, EPA-430/9-78-009 [U.S. Environmental Protection Agency, Office of Water Program Operations, 1978]; Remedial Action at Waste Disposal Sites [Office of Emergency and Remedial Response, U.S. Environmental Protection Agency], in press.)

System Type	Plant Flow, mgd	Construction Costs, $	Operating and Maintenance Costs, $
Conventional	0.1	62,000	3000
	0.3	112,000	5800
	0.6	160,000	8800
	1.0	220,000	12,000
Extended aeration (low flow)	0.01	30,000	4200
	0.03	58,000	7800
	0.06	82,000	12,000
	0.1	110,000	16,000
Pure oxygen	0.1	60,000	6000
	0.3	110,000	1500
	0.6	180,000	25,000
	1.0	275,000	3800
Secondary clarifier (only)	0.1	50,000	2400
	0.3	95,000	4000
	0.6	150,000	6000
	1.0	210,000	8000

oxygen-activated sludge system (1.2 lb oxygen/lb BOD removed, MLSS of 3000 mg/L, F/M ratio of 0.5 lb BOD/day/lb MLSS, and a 2-hour detention time), construction costs include oxygenation basins and covers, dissolution equipment, oxygen generators or liquid oxygen feed/storage facilities, instrumentation, and licensing fees. Finally, for the clarifier, estimates based upon rectangular, flocculator-type clarifier of 600 gal/day/sq ft, construction costs include return and waste pumps (total dynamic head = 10 ft) and spare pumps where necessary (sludge concentration = 1 percent solids).

Trickling Filters

Trickling filters are well suited to treatment of low flow waste streams and are often used as roughing filters to reduce organic loads to a level suitable for activated sludge treatment. Trickling filters are now used with other methods to treat wastewaters from refineries, pharmaceutical plants, and pulp and paper mills, for example.[83] The efficiency of trickling filters in treating refinery and petrochemical wastes ranges from 10 to 20 percent when used as a roughing filter, to 50 to 90 percent when used for secondary treatment.[84] The process is more effective for removing colloidal and suspended materials than for removing soluble matter. Because of the short hydraulic residence time on the filter material, there is usually not enough biodegradation along the filter media to provide the sole means of biological treatment. For concentrated wastes, a high rate of recirculation would be required for a significant reduction of organics. However, the short residence time can be advantageous; trickling filters allow greater variations in the composition of influent waste than do activated sludge or anaerobic digestion. Placed in sequence with activated sludge treatment, the filters could be used to equalize loading variations, while the activated sludge would achieve the high removal efficiencies needed.[85]

The variables that influence design and performance of the trickling filter include the organic and hydraulic load, media type, nature of the waste, pH, and temperature. Trickling filters are classified according to their capability to handle hydraulic and organic loads. Typical acceptable loads for low- and high-rate filters are shown in Table 23. Use of plastic media filters, with low bulk density, has resulted in organic and hydraulic loading rates higher than those achieved with rock media filters. Plastic media filters have generally shown good performance under high BOD loading conditions that would clog conventional systems.[86]

Recirculation is generally required to provide uniform hydraulic loading and to dilute high strength wastewaters. However, there is a limit to the advantages of recirculation. Generally, recirculation rates greater than four times the influent rate do not increase treatment efficiency appreciably.[87] Several recirculation patterns are available. One of the most popular is gravity return of the underflow from the final clarifier to a wet well during periods of low flow, and direct recirculation by pumping filter discharge to the influent.

Several formulas have been proposed to predict BOD removal efficiency based on waste type, influent BOD, hydraulic load, and other factors related to performance. These models present problems because treatability must be determined on a case-by-case basis, and the fact that the models are usually applicable for only very specific conditions.[88]

---

[83] Estimated Waste Treatment Costs, Vol 3; Hardam Azad.

[84] Hardam Azad.

[85] D. H. De Renzo; B. G. Liptak.

[86] Hardam Azad.

[87] B. G. Liptak.

[88] C. J. Velz, "A Basic Law for Performance of Biological Beds," Sewage Works Journal, Vol 20 (1960), p 245; J. E. Germain, "Economical Treatment of Domestic Waste by Plastic-Medium Trickling Filters," J. Water Pollution Control Federation, Vol 28 (1966), p 192; K. L. Schulze, Conference on Biological Waste Treatment (Manhattan College, 1960); W. W. Eckenfelder, "Trickling Filter Design Performance," Transactions of the American Society of Civil Engineers, Vol 128, Part III (1963), p 371.

Trickling filters offer the following advantages: (1) the process is not highly sensitive to shock loads; (2) it is suitable for removing suspended or colloidal matter; and (3) it has good applicability as a roughing filter to equalize organic loads. Disadvantages include the following: (1) the process is vulnerable to below-freezing temperatures; (2) it offers limited treatment capability in a single-stage operation; (3) the potential for odor problems exists; (4) the process has limited flexibility and control; and (5) the process requires long recovery time if disrupted.

Cost estimates for trickling filter package plants are shown in Table 24. These are based on a 40-year service life, an overflow rate of 800 gal/day/sq ft, recycle of three times average flow, and 200-ft maximum diameter. Construction costs include sludge pumps, effluent recycle pumps, clarifier mechanisms, and internal piping.[89]

Rotating Biological Discs

The process is similar to the trickling filter in that the wastes are treated by a fixed-film of biological growth. Disks are mounted on a horizontal shaft, placed in a contour bottom tank, and immersed about 40 percent of the time. When rotated out of the tank, the liquid trickles out of the void space and the biomass is aerated. Rotating biological discs are now being used at full scale to treat wastewaters from the manufacture of herbicides, pharmaceuticals, petroleum, pulp and paper, and pigments. The process has been used only recently in the United States, and is not widespread. However, it is being used more often because of its modular construction, low hydraulic head loss, and adaptability to existing plants.[90] The process can be used for roughing, nitrification, or secondary treatment.

For adequate treatment it is recommended that the process include four stages (discs) per train. At least two parallel trains should be used. Typical design criteria include the following:[91]

Organic loading:	30 to 60 lb BOD/1000 cu ft media (without nitrification) 15 to 20 lb BOD/1000 cu ft media (with nitrification)
Hydraulic loading:	0.75 to 1.5 gal/day/sq ft (without nitrification) 0.3 to 0.6 gal/day/sq ft (with nitrification)
Detention time:	40 to 90 minutes (without nitrification) 90 to 230 minutes (with nitrification)

Based on the design criteria, rotating biological discs can handle organic loads similar to a high-rate trickling filter. The process has several advantages: (1) it is much more flexible than trickling filters; both the intensity of contact between biomass and wastewater, and the aeration rate can be easily controlled by adjusting the rotational speed of the discs; (2)

[89] Innovative and Alternative Technology Assessment Manual.
[90] Innovative and Alternative Technology Assessment Manual.
[91] Innovative and Alternative Technology Assessment Manual.

Table 23

Examples of Acceptable Loads for Low- and High-Rate Trickling Filters
(Adapted from Innovative and Alternative Technology Assessment Manual, EPA-430/9-78-009 [U.S. Environmental Protection Agency, Office of Water Program Operations, 1978].)

	Plastic Media Filter	High Rate, Rock Media	Low Rate, Rock Media
Hydraulic loading m^3/m^2d (gal/day ft^2)	28-56 (700-1400) (Secondary treatment) 93-186 (2300-4600) (Roughing filter)	9.4-37 (230-900)	1.0-3.7 (25-90)
Organic loading kg/m^3d (lb BOD/ day 1000 ft^3)	0.16-0.8 (10-50) (Secondary treatment) 1.6-8 (100-500) (Roughing filter)	0.32-1.0 (20-60)	0.08-0.32 (5-20)
Bed depth, m (ft)	6-9 (20-30)	1-2 (3-6)	1.5-3 (5-10)
Media type	Plastic	Rock, 2.5-22.5 cm (1-5 in.)	Rock, 2.5-22.5 cm (1-5 in.)

Table 24

Estimated Costs for Trickling Filter Package Plant

Flow, mgd	Construction Cost, $	Operation and Maintenance Cost, $
0.1	88,000	4500
0.3	115,000	6400
0.6	160,000	9500
1.0	200,000	12,000

wastewater retention time can be controlled by selecting the appropriate tank size; thus, more thorough treatment can be obtained than with trickling filters; (3) biological discs, unlike trickling filters, rarely clog since shearing forces continuously and uniformly strip excess growth; (4) rotating biological discs can handle larger flow variations and higher organic shock loads than can activated sludge; and (5) modular construction provides flexibility to meet increased or decreased treatment needs.

The disadvantages of the process are as follows: (1) the equipment is vulnerable to temperature changes if not covered, (2) the high organic loads may result in first-stage septicity, and supplemental aeration may be required; (3) odor may be a problem if specific conditions develop; (4) the biomass will be slow to recover if disrupted; (5) the wastes that can be handled have only relatively low strength compared with those that can be treated with activated sludge.

Construction costs are estimated in Table 25; included are rotating biological contactor shafts (standard media, 100,000 sq ft/shaft), motor driver (5 hp per shaft), molded fiber glass covers, and reinforced concrete basins. Loading rate is 1.0 gpd/sq ft.[92]

Table 25

Estimated Construction, Operating, and Maintenance Costs for Rotating Biological Contactors
(Adapted from Innovative and Alternative Technology Assessment Manual, EPA-430/9-78-009 [U.S. Environmental Protection Agency, Office of Water Program Operations, 1978].)

Flow, mgd	Construction Cost, $	Operation and Maintenance Cost, $
0.1	60,000	9500
0.3	150,000	12,000
0.6	330,000	15,500
1.0	550,000	19,000

[92] Innovative and Alternative Technology Assessment Manual.

Anaerobic, Aerobic, and Facultative Lagoons

Lagoons, or waste stabilization ponds, are large shallow basins that rely on long retention times and natural aeration to decompose the waste. In an aerated lagoon, the wastes are artificially aerated with diffused air or mechanical aerators; this differs from activated sludge processes in that there is no sludge biomass recycle. Anaerobic, aerobic, and facultative lagoons have different types of bacteria population. These ponds are more sensitive to high concentrations of inorganics and suspended solids than are other biological methods. Since there is no mixing, suspended solids settle in the pond, creating an excessive load which inhibits benthic microorganisms and creates a sludge blanket along the bottom of the pond. Waste stabilization ponds have been used to treat low strength industrial wastes or to serve as a polishing step for certain waste types. This treatment process is used in food processing industries, paper and pulp mills, textile mills, refineries, and petrochemical plants.[93]

Waste stabilization ponds are constructed similarly -- earthen pits and earthen side levees are most common. For testing leachates, however, the ponds must be lined. The designs of various waste stabilization ponds differ significantly (Table 26). In general, lagoons can treat only low strength waste and therefore are best suited as a polishing step used with other treatment methods. The aerobic lagoon requires the greatest surface area to treat an equivalent waste load. Oxygen transfer depends on the ratio of lagoon surface area to volume (length-to-width ratio should be less than 2:1), temperature, turbulence, and bacterial oxygen uptake. The system has the least tolerance for high organic loads, but benefits from a short detention time.[94] Anaerobic stabilization ponds require significantly less surface area than aerobic and facultative lagoons, and can handle substantially higher organic loads. Deeper lagoons benefit from better heat retention; a length-to-width ratio of no more than 2:1 is recommended. Sludge buildup is much less for the anaerobic pond than for the aerobic; for every pound of BOD destroyed by the anaerobic process, about 0.1 lb of solids is formed; this compares with 0.5 lb for the aerobic lagoon. The major disadvantage of the anaerobic lagoon is that it produces strong odors unless the sulfate concentration is maintained below 100 mg/L.[95]

The facultative lagoon benefits from an aerobic surface layer that oxidizes hydrogen sulfide gas to eliminate odors. It can handle BOD loads that fall between those that can be treated by anaerobic or aerobic lagoons.

Artificial aeration with mechanical or diffused aerators allows for deeper basins and higher organic loads than those for aerobic lagoons. The basins are often designed for partial mixing only, so that anaerobic decomposition occurs on the bottom. While lagoon systems cannot withstand the higher organic loads tolerated by activated sludge, operating costs are significantly less. In general, several lagoons in series are more efficient than one lagoon since they can reduce short-circulation and lead to increased organic removal efficiency.

---

[93]D. H. De Renzo; N. L. Nemerow.
[94]Estimated Waste Treatment Costs, Vol 3; B. G. Liptak.
[95]B. G. Liptak.

Table 26

Design Criteria for Waste Stabilization Ponds
(Adapted from *Selected Biodegradation Techniques for Treatment and Ultimate Disposal of Organic Materials*, EPA 600/2-79-006 [U.S. Environmental Protection Agency, 1979]; B. G. Liptak, ed., *Environmental Engineer's Handbook, Vol I: Water Pollution* [Chilton Book Co., 1974]; Metcalf and Eddy, Inc., *Wastewater Engineering: Collection, Treatment, and Disposal* [McGraw-Hill Book Co., 1979].)

	Aerobic	Facultative	Anaerobic	Aerated
Depth, ft	0.9 to 1.8	1.8 to 4.5	7.5 to 18	3 to 18
Organic load, lb BOD/acre/day	89.3 to 178.6	8.93 to 89.3	178.6 to 1786	8.93 to 267.9
Detention time typical, days	2 to 6	7 to 30	30 to 50	3 to 10
Influent BOD, mg/L	200	200 to 500	500 and up	200 to 500
Flow regime	Intermittently mixed	Mixed surface layer	Not mixed	Completely mixed
Principal conversion product	Algae, CO_2, bacteria	Algae, CO_2, CH_4, bacteria	CO_2, CH_4, bacteria	CO_2, bacteria
Algal concentration, mg/L	40 to 100	10 to 80	0 to 5	--
Operating pH	6.5 to 10.5	6.5 to 9.0	6.8 to 7.2	6.5 to 8.0
Effluent suspended solids, mg/L	10 to 140	40 to 100	80 to 160	80 to 250

Lagoon treatment has the following advantages: (1) operating costs are low compared with those of other biological treatment methods; (2) the system produces cost-effective treatment for small volume flows; and (3) waste stabilization ponds require minimal energy and are quite reliable. Disadvantages are: (1) the process tolerates low strength wastes only; (2) it is intolerant of suspended solids and metals; (3) it requires large land area per unit flow volume; (4) performance is markedly affected by temperature (not suitable in freezing temperatures); (5) the system has limited flexibility; and (6) volatile gases may be emitted.

The cost of lagoon construction is quite site-specific, depending largely on flow rates, loading factors, site topography, and land cost. The cost of lagoon construction is primarily a function of lagoon area requirements, which are directly related to flow and load. The estimates in Table 27 are given for rough comparisons only. To extrapolate detention times different from those of the examples, the following formula can be used:

$$\text{New cost estimates} = \text{estimate given} \times \frac{\text{new design detention time}}{\text{example detention time}}.$$

Table 27

Estimated Costs of Different Types of Lagoon Leachate Treatment Systems (Adapted from Innovative and Alternative Technology Assessment Manual, EPA-430/9-78-009 [U.S. Environmental Protection Agency, Office of Water Program Operations, 1978].)

Lagoon Type	Plant Flow, mgd	Construction Cost, $	Operation and Maintenance Cost, $
Anaerobic	0.1	210,000	6000
	0.3	480,000	12,000
	0.6	820,000	20,000
	1.0	1,150,000	26,000
Facultative	0.1	80,000	2000
	0.3	170,000	3800
	0.6	280,000	6000
	1.0	400,000	8000
Aerated	0.1	52,000	4000
	0.3	65,000	6200
	0.6	80,000	9500
	1.0	100,000	12,000

*The figures do not include expenses for buying land nor providing a bottom liner. Roughly level terrain is assumed.

For different loading factors (facultative lagoons), the following formulas can be used:

$$\text{Warm climate: } \frac{\text{new cost}}{\text{estimate}} = \frac{\text{estimate}}{\text{given}} \times \frac{\text{40 lb BOD/acre day}}{\text{new design loading}}$$

$$\text{Cool Climate: } \frac{\text{new cost}}{\text{estimate}} = \frac{\text{estimate}}{\text{given}} \times \frac{\text{20 lb BOD/acre day}}{\text{new design loading}}$$

Cost estimates for the anaerobic lagoon are based on an average detention time of 35 days and include service roads and grading, excavating, and other earth work, but no pumping equipment. Facultative lagoon estimates are for a warm climate, a loading of 40 lb BOD/acre/day and a water depth of 4 ft. Estimates for aerated lagoons assume a 7-day detention time, 15-ft depth, and aeration equipment requiring 36 hp/mgd. Lagoon systems are favored for leachate treatment because of their low cost and flexible operation.

Land Application of Municipal Landfill Leachates

Land application involves using plants, the soil surface, and soil matrix for wastewater treatment. Land application of wastewater has been practiced for centuries, but has only recently become recognized in the United States because of the emphasis on water and nutrient recycling. The three principal processes for land application of wastewater are irrigation, rapid infiltration, and overland flow.[96] Other processes which are generally less adaptable to large-scale use are wetland application, subsurface application and aquaculture.[97] Typical design features, major site characteristics, and the expected quality of treated wastewaters are summarized in Tables 28, 29, and 30.

Irrigation is the land-treatment process used most often today. The effluent is treated by chemical, physical, and biological means as it percolates through the soil. Wastewater can be applied by sprinkling (with its increased aeration and energy cost), or by surface techniques such as ridge and furrow or border strip flooding. Application rates of 0.9 to 2.9 in./week are often used for crop irrigation, but higher rates of application are possible (2.3 to 3.9 in./week) if water tolerant, low-value grasses are used. Table 31 lists criteria that should be considered when sites for land irrigation of wastewater are being selected.

Rapid infiltration systems apply effluent to the soil at high rates (3.9 to 81.9 in./week) by spreading in basins or by sprinkling for rapid groundwater recharge. Natural treatment is followed by pumped withdrawal, recover

[96] Metcalf and Eddy, Inc.

[97] R. K. Bastion and S. C. Reed, Aquaculture Systems for Wastewater Treatment: Seminar Proceedings and Engineering Assessment, EPA-430/9-80-006 (U.S. Environmental Protection Agency, 1979), 485 pp; S. C. Reed and R. K. Bastion, Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, EPA-430/9-80-007 (U.S. Environmental Protection Agency, 1980), 126 pp.

Table 28

Comparison of Site Characteristics for Land-Treatment Processes (Adapted from Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment, and Disposal [McGraw-Hill Book Co., 1979].)

Constituent	Irrigation* Average	Irrigation* Maximum	Rapid Infiltration** Average	Rapid Infiltration** Maximum	Overland Flow+ Average	Overland Flow+ Maximum
BOD	<2	<5	2	<5	10	<15
Suspended solids	<1	<5	2	<5	10	<20
Ammonia nitrogen as N	<0.5	<2	0.5	<2	0.8	<2
Total nitrogen as N	3	<8	10	<20	3	<5
Total phosphorus as P	<0.1	<0.3	1	<5	4	<6

Note: All values in mg/L.
*Percolation of primary or secondary effluent through 1.5 m of soil.
**Percolation of primary or secondary effluent through 4.5 m of soil.
+Runoff of comminuted municipal wastewater over about 45 m of slope.

using underdrains, or discharge to surface water courses. The water is treated as it moves through the soil matrix.

In the overland flow process, wastewater is applied to the upper reaches of sloped terraces and is treated as it flows over vegetated areas to runoff collection ditches. Overland flow is used either as a secondary treatment process where discharge of a nitrified effluent of low BOD is acceptable, or as a polishing step. Polishing of secondary effluent allows high flow rates (5.9 to 15.6 in./week).

The use of wetlands or aquaculture for wastewater treatment has received attention recently.[98] In some cases, the primary objective is to produce biomass or other beneficial products by using wastewater nutrients and BOD. In other cases, the treatment of the waste is the primary incentive. Removal efficiencies for secondary effluents are 70 to 96 percent BOD, 60 to 90 percent suspended solids, 40 to 90 percent nitrogen, and 10 to 50 percent phosphorus. Typical land area requirements are from 30 to 60 acres/mgd for natural wetlands and 23 to 37 acres for specially constructed wetlands receiving primary effluent.[99]

Exchangeable cations, particularly sodium, calcium, and magnesium ions in the wastewater are especially important in determining whether wastewater is acceptable for land treatment. High sodium concentrations in clay-bearing

[98] R. K. Bastion and S. C. Reed; S. C. Reed and R. K. Bastion.
[99] R. K. Bastion and S. C. Reed.

Table 29

Comparison of Design Features for Land-Treatment Processes
(Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering: Collection, Treatment, and Disposal* [McGraw-Hill Book Company, 1979].)

Feature	Irrigation	Rapid Infiltration	Overland Flow	Wetland Application	Subsurface Application
Application techniques	Sprinkler or surface*	Usually surface	Sprinkler or surface	Subsurface piping	
Annual applicate rate, m	0.6-6.0	6-120	3-20	1-30	2-25
Field area required, ha**	22-226	1-22	10-44	4-113	5-56
Typical weekly application, cm	2.5-10	10-210	6-15+ 15-40++	2.5-60	5-50
Minimum preapplication treatment provided	Primary sedimentation	Primary sedimentation	Screening and grit removal	Primary sedimentation	Primary sedimentation
Disposition of applied wastewater	Evapotranspiration and percolation	Mainly percolation	Surface runoff and evapotranspiration with some percolation	Evapotranspiration percolation, and runoff	Percolation with some evapotranspiration
Need for vegetation	Required	Optional	Required	Required	Optional

*Includes ridge and furrow and border strip.
**Field area in hectares not including buffer area, roads, or ditches for 0.044 m^3/day (1 Mgal/day) flow.
+Range for application of screened wastewater.
++Range for application of lagoon and secondary effluent. Depends on the use of the effluent and the type of crop.

soils disperse the soil particles and break down soil structures, decreasing the soil's permeability. The sodium absorption ratio (SAR) was developed to give guidance on permeability:

$$SAR = \frac{Na}{(Ca + Mg/2)} \qquad \text{[Eq 5]}$$

where: Na = sodium, meq/L
Ca = calcium, meq/L
Mg = magnesium, meq/L

SAR values above 9 may indicate that the permeability and structure of fine-textured soils have been adversely affected. High sodium levels are also toxic to plants, but decreases in soil permeability generally occur first and have greater effects.

Costs of land application are generally moderately low if land values are not included. For a 10-acre site, solid-set spray irrigation systems can be built for about $31,000, including all pipes and pumps. Operation and maintenance costs on such a system are estimated at $3500 per year. Land application has been used on landfill leachate with some success.

Table 30

Comparison of Expected Quality of Treated Water from Land-Treatment Processes (All Values in mg/L)
(Adapted from Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment, and Disposal [McGraw-Hill Book Co., 1979].)

Constituent	Irrigation* Average	Irrigation* Maximum	Rapid Infiltration** Average	Rapid Infiltration** Maximum	Overland Flow+ Average	Overland Flow+ Maximum
BOD	<2	<5	2	<5	10	<15
Suspended solids	<1	<5	2	<5	10	<20
Ammonia nitrogen as N	<0.5	<2	0.5	<2	0.8	<2
Total nitrogen as N	3	<8	10	<20	3	<5
Total phosphorus as P	<0.1	<0.3	1	<5	4	<6

*Percolation of primary or secondary effluent through 5 ft of soil.
**Percolation of primary or secondary effluent through 15 ft of soil.
+Runoff of comminuted municipal wastewater over about 148.5 ft of slope.

[100] J. C. S. Lu et al., "Leachate Production and Management from Municipal Landfills: Summary and Assessment," Land Disposal: Municipal Solid Waste, EPA-600/9-81-002a (U.S. Environmental Protection Agency, 1981), pp 1-17.

Table 31

Site-Selection Factors and Criteria for Effluent Irrigation
(Adapted from Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment, and Disposal [McGraw-Hill Book Company, 1979].)

Factor	Criterion
Soil:	
Type	Loamy soils are preferred, but most soils from sands to clays are acceptable.
Drainability	Well-drained soil is preferred; consult experienced agricultural advisors.
Depth	Uniformly 5 to 6 ft or more throughout sites is preferred.
Groundwater:	
Depth to groundwater	A minimum of 5 ft is preferred. Drainage to obtain this minimum may be required.
Groundwater control	Control may be necessary to ensure renovation if the water table is less than 10 ft from the surface.
Groundwater movement	Velocity and direction of movement must be determined.
Slopes:	Up to 20 percent are acceptable with or without terracing.
Underground formations:	Formations should be mapped and analyzed with respect to interference with groundwater or percolating water movement.
Isolation:	Moderate isolation from public is preferred; the degree of isolation depends on wastewater characteristics, method of application, and crop.
Distance from source of wastewater:	An appropriate distance is a matter of economics.

4 APPLICATION OF AVAILABLE TECHNOLOGY TO LANDFILL LEACHATES

Laboratory Studies

Several major studies of landfill leachate treatment systems have been made using biological units with and without physical/chemical treatment. These studies had varying degrees of success.

Cook and Foree, in a bench-scale study, evaluated the treatability of sanitary landfill leachates using aerobic digesters with activated sludge recycle and selected chemical additions.[101] Treatment for polishing the effluent from the aerobic and aerated biological systems was also evaluated. After preliminary studies, five activated sludge systems were run in parallel. The reactors were aerated and completely mixed. Activated sludge from a previous experiment was used to start up the systems. The units were operated for 45 days at the loadings indicated in Table 32. Nutrient additions were 500 mg/L nitrogen and 100 mg/L phosphorus; as a pretreatment, 250 mg of hydrated lime per liter were added. The additions, retention times, loading, and characteristics of the raw leachate and the effluent (mixed liquors) from the reactors are given in Table 32.

All reactors with a 10-day biological solid retention time removed COD effectively. More than 99 percent COD removal efficiency was maintained by activated sludge treatment with no chemical addition (Unit 1, Table 32). The reactor with the 5-day detention time began to fail rapidly after about 25 days of operation, as indicated by the decrease in COD removal efficiency shown in Figure 5. Lime and nutrient additions were not beneficial. The effluent from activated sludge units had good settling characteristics and very high nutrient removal efficiencies.

Polishing the effluent from these digesters by carbon absorption removed 50 to 70 percent of the remaining COD, giving 99 percent or better COD removal in all cases. Polishing with 5 percent sodium hypochlorite did not greatly affect the residual COD levels and did not remove color well. Chemical additions to the raw leachates (mixtures of hydrated lime, alum, ferric chloride and sulfate, Purofloc A-23 polyelectrolyte, and sodium hydroxide) very effectively removed suspended solids (70 to 90 percent), but had very little effect on COD (<15 percent removal).

In a second phase of this study Foree and Reid examined the anaerobic stabilization of landfill leachates by conventional anaerobic digestion and anaerobic filtration.[102] Both effectively and efficiently stabilized raw sanitary landfill leachates. Table 33 indicates that Digester 4 was the most effective of the five included in the experiment. It had a detention time of 20 days at 95°F with no nutrient or lime additions. This digester had a COD

[101] E. N. Cook and E. G. Foree, "Aerobic Biostabilization of Sanitary Landfill Leachate," Journal of the Water Pollution Control Federation, Vol 46, No. 2, pp 380-392.

[102] E. G. Foree and V. M. Reed, Anaerobic Biological Stabilization of Sanitary Landfill Leachates, UTK TR65-73-CE-17 (University of Kentucky, 1973), 43 pp.

Table 32

Characteristics of Leachate, Mixed Liquors, and Effluents from Five Aerobic Digestors

(From E. N. Cook and E. G. Foree, "Aerobic Biostabilization of Sanitary Landfill Leachate," Journal of Water Pollution Control Federation Vol 46, No. 2, p 384).

Characteristics	Leachate	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Additions to leachate	--	--	Lime	Lime and Nutrients	Nutrients	--
Detention time, days		10	10	10	10	5
Loading (lb COD/100 cu ft/day)	--	98.5	98.5	98.5	98.5	197
COD, mg/L	15,800	360	340	290	310	8450
COD removal efficiency, percent	--	97.6	97.8	98.1	98.0	46.5
BOD_5, mg/L	7100	26	23	11	10	3400
Total carbon, mg/L	4920	310	300	88	90	2980
Total organic carbon, mg/L	4600	140	130	76	76	1810
Total inorganic carbon, mg/L	320	160	170	12	14	1170
MLSS, mg/L	550	5950	7370	7270	7070	4490
MLVSS, mg/L	310	4410	4930	4770	5020	3270
Percent MLVSS	57.1	74.3	66.8	65.7	70.9	73.0
TSS (settled effluent mg/L)	--	56	39	56	77	4490
VSS (settled effluent mg/L)	--	41	24	38	57	3270
Percent VSS	--	73.2	61.3	66.7	73.4	73.0
Sludge volume index	--	55	41	39	45	122
pH (avg.)	5.4	8.4	8.4	7.6	7.6	8.0

Table 32 (Cont'd)

Characteristics	Leachate	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Alkalinity (as $CaCO_3$), mg/L	3280	670	680	78	72	2630
Acidity (as $CaCO_3$), mg/L	1580	--	00	8	7	--
TKN, mg/L	280	16	13	21	23	118
Ammonia nitrogen, mg/L	10	8.5	6.5	3.4	4.1	72
Nitrate nitrogen, mg/L	19	4.3	4.1	24	35	3.9
Total phosphorus, mg/L	13	0.14	0.14	0.26	0.41	0.95
Orthophosphorus, mg/L	8.7	0.016	0.040	0.050	0.118	0.106
Color	450	360	320	150	180	--
Total iron, mg/L	240	<10	<10	<10	<10	--
Calcium, mg/L	1200	39	20	420	430	--
Magnesium, mg/L	170	140	120	130	140	--
Chloride, mg/L	540	510	520	1650	1530	--
Conductivity, µmhos/cm	5800	2900	3850	4800	4800	--

Table 33

Characteristics of Leachate, Mixed Liquors, and Filter Effluent (From D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Waste [Noyes Data Corp, 1978].)

Characteristics	Leachate	Anaerobic Digester Mixed Liquors					Filter Effluent
Unit number	--	1	2	3	4	5	--
Additions to leachate	--	Nutrients	Nutrients	Lime	--	Nutrients	--
Detention time (θ, days)	--	20	20	20	20	10	10
Loading (lb COD/1000 cu ft/day)	--	40.1	40.1	40.1	40.1	80.2	80.2
Temperature (°C)	--	35	20	35	35	35	35
Total COD, mg/L	12 900	1688	3612	2038	1278	2312	507
Soluble COD, mg/L	--	598	2859	836	629	1056	--
COD removal efficiency, percent	--	95.3	77.4	93.4	95.0	91.8	96.1
Total carbon, mg/L	4920	987	1381	696	656	901	736
Organic carbon, mg/L	4600	255	725	225	175	275	200
TSS, mg/L	545	2903	1867	3771	2730	2754	40
VSS, mg/L	311	1025	784	1281	785	1035	30
Volatile acids (mg/L as acetic)	--	120	144	120	144	480	24
pH	5.45	7.50	7.25	7.46	7.50	7.46	7.24
Alkalinity (mg/L as $CaCO_3$)	3280	2960	3100	1860	2020	2720	1940
TKN, mg/L	281	560	530	230	170	535	181
NH_3-N, mg/L	10	515	463	136	137	417	156
Total soluble phosphorus, mg/L	12.5	--	5.3	0.9	0.55	2.25	0.42
Orthophosphate, mg/L as P	8.68	2.2	1.2	0.3	0.2	1.7	0.3
Color (color units)	450	350	350	150	175	300	200

Note: Data from 28-day run under equilibrium conditions.

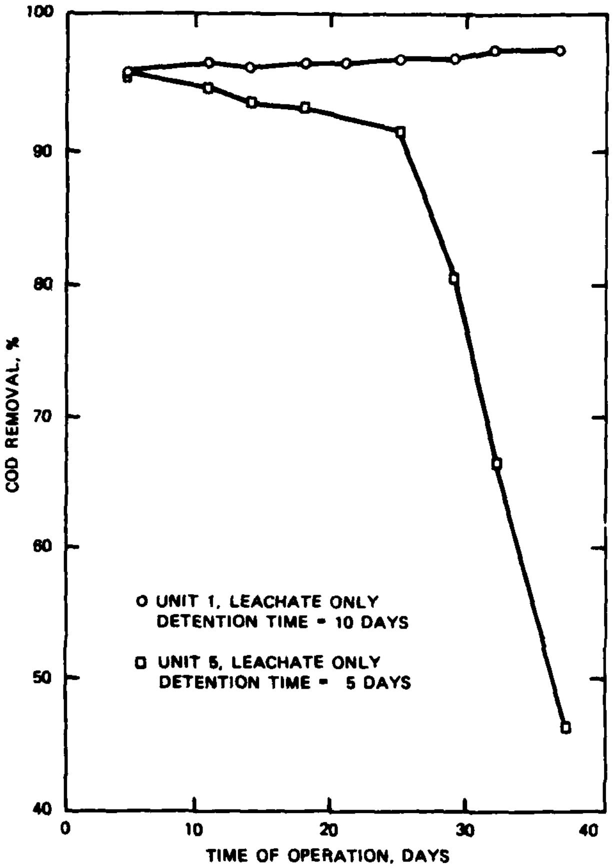


Figure 5. Activated sludge COD removal efficiencies for detention times of 5 and 10 days. (From E. N. Cook and E. G. Foree, "Aerobic Biostabilization of Sanitary Landfill Leachate," Journal of the Water Pollution Control Federation, Vol 46, No. 2, pp 386).

removal efficiency of over 95 percent and methane production of (0.2 cu ft/gal). This system had a stable microbial population, efficient nutrient use, and an optimum pH. Digesters 1, 3, and 5 with nutrient and/or lime addition and 10- or 20-day detention times at 95°F also performed adequately, but somewhat less satisfactorily. Digester 2, which was operated at 65°F was least satisfactory, but its poor performance could be predicted from online digesters running at 65°F.

An anaerobic filter was made from a 6-ft by 6-in.-diameter Plexiglas column which was filled with crushed limestone and sealed at the ends. It had a total volume of 1.16 cu ft with a 0.5 cu ft void space. Leachate was pumped continuously into the bottom of the filter at a rate of 0.4 gal/day. COD removal efficiency was 96 percent, and methane production was 0.65 cu ft/gal of leachate produced. Nutrients were used efficiently, an optimum pH was maintained, and the effluent was odorless. Effluent polishing with an activated sludge unit increased the overall COD removal only to 96.5 percent.

The advantages of the anaerobic system over the aerobic activated sludge system studied by Cook and Foree were the net production of methane, lower biological solids production, and the absence of an oxygen requirement, which made aeration equipment unnecessary. The results of both experiments are compared in Table 34. Foree and Reid summarize their results as follows: "The activated sludge unit with effluent polishing provides the most effective treatment. However, this system would generally be more elaborate and more expensive than any of the other treatment systems evaluated. The performance of an anaerobic filter followed by a small activated sludge unit would compare favorably with that of the larger aerobic system. The filter and digester rank third in treatment efficiency." Unfortunately, nonaerated lagooning systems with longer detention times were not evaluated.

Preliminary laboratory-scale results from Boyle and Ham indicate that biological treatment of sanitary landfill leachates effectively removes a substantial portion of the organic pollutants.[103] Both aerobic and anaerobic treatment gave over 90 percent BOD reduction. Anaerobic treatment was effective with hydraulic retention times of 10 days or more and temperatures between 73.4 and 86°F. A temperature coefficient averaging 1.11 was estimated over this temperature range for anaerobic BOD removal rates in laboratory vessels. Temperatures below 73.4°F again were the main cause of system inefficiency. Boyle and Ham's digesters were run down to 51.8°F. Heavy metals were present in the raw leachate but had no apparent effect on the activity of the anaerobic digesters; the units operated for more than 14 months without noticeable deterioration of gas generation rates or COD reduction. Aerobic polishing of the anaerobic effluents produced BOD vales (40 mg/L) that would permit surface water discharge.

In another bench-scale experiment, completely mixed, aerated vessels were operated on a fill and draw basis with landfill leachates. Detention times of only 5 days with loading of less than 0.5 kg COD/m^3/day gave 93 percent COD removal efficiencies over a 6-week period. Shorter detention times or higher loadings lowered removal efficiencies considerably. The anaerobic treatment systems were recommended. The aerobic systems required more energy and foamed excessively. Furthermore, the solids/liquids separation were poor in bench-scale units. No passive (nonaerated) aerobic systems were included in this study.

In addition, Boyle and Ham showed that leachate could be added to domestic wastewater in an extended aeration, activated sludge plant. The leachate level could be at least 5 percent by volume (leachate COD = 10,000 mg/L) without seriously impairing effluent quality (Table 35). More than 5 percent leachate by volume resulted in substantial solids production, increased oxygen uptake rates, and poorer mixed liquor separation in the plant.

---

[103] Estimating Waste Treatment Costs, Vol 3: Cost Curves Applicable to 2,500 gpd to 1.0 mgd Treatment Plants, EPA-600/2-79-162c (U.S. Environmental Protection Agency, Municipal Environment Research Laboratory, 1979).

Table 34

Summary of Performance Characteristics of Various Treatment Processes for Sanitary Landfill Leachate (From D. H. De Renzo, Unit Operations for Treatment of Hazardous Industrial Wastes [Noyes Data Corp., 1978].)

Process	Temp, °F	Detention Loading, lb/1000 cu ft/day	Detention time, days	COD Removal Efficiency, Percent	COD mg/L	TSS mg/L	pH
Anaerobic digester*	95	40	20	95.3	598	2903	7.5
Anaerobic digester*	95	80	10	91.8	1056	2754	7.5
Anaerobic digester*	65	40	20	77.4	2859	1867	7.3
Anaerobic filter	95	80	10	96.1	507	40	7.2
Anaerobic filter + activated sludge	95	80	10	96.9	353	68	8.9
Activated sludge*	71.6	100	10	97.6	360	56	8.4
Activated sludge*+ activated carbon	71.6	100	10	99.2	130	0	8.9
Physical/chemical* *(alum + lime floc)*				13.2	14 800	111	6.5

*With effluent solids separation.

Table 35

Effects of Landfill Leachate Influent Additions on Extended Aeration Sewage Treatment Plant Effluents
(From Estimating Waste Treatment Costs, Vol 3: Cost Curves Applicable to 2,500 gpd to 1.0 mgd Treatment Plants, EPA-600/2-79-162c [U.S. Environmental Protection Agency, Environmental Research Laboratory, 1979].)

	COD			Solids Produced		
Percent Leachate	mg/L	Percent Increase	BOD, Percent Increase	mg/day	Percent Increase	O_2 Uptake, Percent Increase
0	30	--	--	82	--	--
1	24	0	0	110	35	4.5
2	31	3	8	148	80	77
5	38	26	53	178	117	241
10	59	97	160	332	305	440
20	113	276	1040	722	780	840

Ho, Boyle, and Ham also studied bench-scale chemical treatment of sanitary landfill leachates.[104] Two chemicals were tried as chemical precipitants: lime and sodium sulfite. Lime gave better treatment, but neither performed satisfactorily on raw leachates. Iron and color were removed at high chemical doses; but there was no significant COD removal, and a large amount of sludge was produced. Alum and ferric chloride as chemical coagulants gave quite similar results. Both produced very large amounts of sludge. Excellent removal of iron and color was noted, but little COD and dissolved solids removal occurred -- even at very high doses. For example, at pH 7.0, only 16 percent COD removal was produced with a ferric chloride dose of 1000 mg/L. Alum did not reduce COD at all.

Chlorine, calcium hypochlorite, potassium permanganate, and ozone were also tried as chemical oxidants in raw leachate treatment. COD reduction was evident with all oxidants, but again very high doses were required. At 1200 mg/L chlorine, removal of COD was 25 percent; at 8000 mg/L calcium hypochlorite, 48 percent; at 10 000 mg/L potassium permanganate, 20 percent; and after 4 hours of ozone treatment, the COD removal was only 37 percent. Chloride content was increased greatly by the chlorine and hypochlorite treatments, and hardness increased significantly during hypochlorite treatment. Neither ozone nor hypochlorite produced much sludge. None of the oxidants was very promising in the primary treatment of high strength leachates.

---

[104] S. Ho, W. C. Boyle, and R. K. Ham, "Chemical Treatment of Leachates from Sanitary Landfills," Journal of Water Pollution Control Federation, Vol 46, No. 7 (1974), pp 1776-1791.

Boyle and Ham also evaluated the use of activated carbon with landfill leachate.[105] Granular activated carbon at doses of at least 400 mg/L were necessary to obtain maximum COD removal in a 30-minute period of treatment for landfill leachate. Sample laboratory column tests were encouraging, giving significant color and odor reduction after a detention time of four minutes, and removal of all color and odor, 55 percent COD, and 60 percent iron after about 20 minutes. The authors concluded that the performance of a given chemical/physical treatment option may be expected to vary significantly as the characteristics of the leachate change. Chemical processes are quite specific in their capability to remove contaminants from leachates. It seems, therefore, that chemical treatment methods may be tailored most advantageously to complement biological treatment of sanitary landfill leachates.

Chian and DeWalle have made extensive studies of sanitary landfill leachate composition[106] and treatment techniques.[107] They studied the COD removal efficiencies of an anaerobic filter; benchtop, aerated digesters; and an activated-sludge unit treating combined landfill leachate and municipal sewage. The effectiveness of physical/chemical treatment of raw and biologically pretreated leachates was also addressed.

A completely mixed anaerobic filter, in which the influent organic matter concentration was diluted with recirculated effluent, effectively removed organic matter concentrations in high-strength municipal solid waste leachate over a range of organic loadings and shock loads.[108] Recirculation of effluent can effectively increase the acidic pH of the feed to a value close to the optimum for the anaerobic organisms in the filter. Thus, it is not necessary to add the costly buffer solutions required in a plug-flow filter. This step also dilutes the influent, greatly lessening the probability of toxic levels of ammonia or high COD. In the anaerobic filter, complex organics in the feed are hydrolyzed first by acid fermenting bacteria to free volatile fatty acids. These are primarily acetic and butyric acids, which in turn are removed by methanogenic bacteria (converted to methane and carbon dioxide). The methane in the generated gases accounted for 93 percent of the COD removal of the unit, while a solids balance indicated that only 0.012 g of volatile suspended solids was produced per gram of COD removed. Because of the low solids production and the initial seeding of the unit with digested sludge, no nutrient additions were required during the 519-day operating period -- even though the COD:P and COD:N ratios in the feed were as high as 4360:1 and 39:1, respectively. Although some possible heavy metal toxicity was observed (because of high copper concentrations building up in the recirculated system), a single precipitation of heavy metals by sodium sulfide addition (75 mg/L) to the feed solved the problem, and the filters rapidly returned to normal. A high percentage of organic matter removal was observed when the hydraulic detention time was maintained above 7 days. Shorter detention times produced considerably lower removal percentages.

Aerated digester treatment of high strength leachate (COD of 57 900 mg/L) removed between 93 and 96.8 percent of the organic matter. This was done without any pretreatment of the influent at hydraulic detention times ranging

---

[105] Estimating Waste Treatment Costs, Vol 3.
[106] E. S. K. Chian and F. B. DeWalle, Vol I.
[107] E. S. K. Chian and F. B. DeWalle, Vol II.
[108] E. S. K. Chian and DeWalle, Vol II.

from 85.7 days to as few as 7 days, and loadings varying between 0.67 kg COD/m^3/day for the 85.7-day unit to 5.0 kg COD/m^3 for the 7-day unit (Table 36). Nitrogen and phosphate addition increased the efficiency of digesters with short detention times and high loading. Units with a retention time of 85.7 days and 60 days could be operated with a COD:P ratio of 1540:1 in the feed solution, but the ratio in the influent of the 30-day unit had to be at least 300:1. Stopping nutrient addition at a COD:P ratio of 165:1 to the units operated at short detention times (less than 30 days) caused an immediate increase in effluent organic matter, a decrease in biological mixed liquor volatile suspended solids, and a deterioration of the sludge settling characteristics. All units had high removals of heavy metals, especially iron (>99.9 percent), calcium (99.3 percent), and magnesium (75.9 percent). Lower removal efficiencies were observed for sodium (24.1 percent) and potassium (17.0 percent). The TOC and COD results are summarized in Table 36.

High strength leachates could not be effectively treated by physical/chemical treatment methods such as activated carbon adsorption, chemical precipitation, or chemical oxidation.[109] Activated carbon had a relatively low sorptive capacity when used to treat high strength leachates. Free volatile fatty acids, the major constituents of such leachates, have a relatively low sorptive capacity; even lower capacities were found for the nonfatty-acid fraction in leachate using activated carbon adsorption isotherms. Although an initial removal rate as high as 72 percent was obtained in activated carbon columns with diluted leachate, much lower removal percentages were observed after passage of several bed volumes. Almost complete breakthrough occurred after fewer than 200 bed volumes. The column studies also illustrated the lower removal rate for the nonfatty acid fraction in leachates. Additional problems with activated carbon treatment resulted because head loss developed rapidly in the column with the formation of iron precipitates; although most of these precipitates were removed in the first backwash, difficulty was again encountered in subsequent runs on the same columns.

Substantially higher adsorptive capacities of activated carbon were found for biologically pretreated leachate. Removal of biodegradable organics with an anaerobic filter increased the adsorptive capacity of the carbon columns by 50 percent. Aerated digester treatment of the anaerobic filter effluent further removed low molecular weight organics, resulting in an adsorption capacity of 0.174 mg TOC/mg carbon, a value about 2.5 times that observed for untreated leachate. Batch sorption tests showed that color and aromatic hydroxyls are removed at lower carbon dosages than are high-molecular-weight carbohydrate-like materials. The highest removal rates were observed for fulvic acid-like organics of intermediate molecular weight. The increase in removal rates of organics in anaerobic filter effluent treated by aerated digesters was attributed to the higher adsorption characteristics of the low-molecular-weight organics.

Organic matter removal by lime precipitation, both before and after aeration, produced removal rates as low as 20 to 25 percent; this removal was obtained only with excessively large dosages. Other physical/chemical methods tested, such as ozonation and chlorination, resulted in similarly low organic matter removal rates. These results clearly show that physical/chemical treatment methods are not feasible for high-strength leachates and that

[109] E. S. K. Chian and F. B. DeWalle, Vol II.

Table 36

Characteristics of Effluent From Aerated Digester With Sufficient Nutrient Addition
(From *Evaluation of Leachate Treatment; Vol II: Biological and Physical-Chemical Processes*, EPA-600/2-77-186b [U.S. Environmental Protection Agency, 1977].)

Characteristics	Units 1, 2, and 3	Unit 1	Unit 2	Unit 3	Units 4, 5, and 6	Unit 4	Unit 5	Unit 6
Retention time, days	--	85.7	60	30	--	30	15	7
TOC, mg/l	19 400	160	180	240	11 773	210	310	380
TOC removal, percent	99.12	99.1	98.8	--	98.2	97.4	97.4	96.8
COD, mg/l	57 900	415	540	666	35 237	536	822	1034
COD removal, percent	99.3	99.1	98.9	--	--	98.5	97.7	97.1
MLVSS, mg/l	--	8000	9000	10 000	--	9500	11 500	13 500
pH	5.4	8.77	8.72	8.7	5.7	8.8	8.6	8.5

extensive biological pretreatment is required. Of all physical/chemical methods tested, activated carbon treatment produced the highest organic matter removal rates.

Reverse osmosis using cellulose diacetate and a special thin, two-layered membrane was attempted on raw leachate. After the pH of the leachate was adjusted to 8.0 with NaOH to increase the disassociation of the organic acids, and at a pressure of 600 psi, both membrane systems provided adequate separation (>95 percent) on high-strength leachates (TOC = 13 000 to 18 500 mg/L). However, fouling of the membrane was a serious problem. Successive runs, even after washing, showed fluxes of less than 25 percent of the original; additional runs decreased the flux even more. Therefore, the method seems to be completely impractical for landfill leachates -- unless suspended solids, colloidal materials, and iron hydroxides are effectively removed before reverse osmosis.

Chian and Dewalle also studied different physical/chemical treatment methods for polishing the effluent from the aerobic digester discussed above.[110] While only 48 percent of the TOC was removed after a 3-hour period of ozonation, activated carbon columns were able to remove 86 percent with an empty bed detention time of 3.7 minutes. A weak-base anion exchange resin provided a 59 percent initial COD removal, while 82 and 85 percent of the COD was initially removed using strong-base anion exchange resins. Reverse osmosis was the only process able to remove 91 to 96 percent of the salts initially present at a total dissolved solids concentration of 6200 mg/L. The organic matter removal by reverse osmosis ranged from 85 to 97 percent; these removal rates were not improved by ion exchange or activated carbon pretreatment. The flux through the membranes was relatively high, and membrane fouling was relatively insignificant if the suspended solids were removed from the influent. Sand filtration or chemical precipitation are a necessary pretreatment for reverse osmosis units.

Combined Treatment of Leachate and Municipal Sewage

A conventional plugflow, activated sludge unit receiving municipal sewage effectively treated a high strength leachate containing high concentrations of free volatile fattyacids such as acetic and butyric acids.[111] Immediately after the leachate was added to the stable sewage treatment unit, some deterioration in effluent quality was observed. But after acclimation, effluent BOD values of the test unit receiving low leachate additions were generally comparable to those of the control unit. While BOD values were not greatly affected, COD concentrations showed a gradual increase with increasing leachate addition, indicating that the larger quantities of refractory organics in the influent leachate were being released from the test unit. The test unit could not treat the high-strength leachate at 4 percent or more of the influent flow rate. Above 4 percent leachate, increasing BOD concentrations appeared in the effluent, and sludge characteristics deteriorated.

[110]E. S. K. Chian and F. B. DeWalle, Vol II.
[111]E. S. K. Chian and F. B. DeWalle, Vol II.

Pilot and Full-Scale Studies

The first full-scale demonstration of a mixed municipal landfill leachate treatment plant was installed at the GROWS landfill in Bucks County, PA.[112] The system was designed for a 100-gpm flow rate. A schematic flow diagram of the current plant is shown in Figure 6. The system was built so that different arrangements of the treatment modules could be used with minor modifications. Four different treatment configurations have been tested extensively.

Configuration No. 1 consisted of lime addition, sedimentation, air-stripping, neutralization (with acid), nutrient supplementation, and activated sludge treatment (Figure 6). Results of 10- and 13-month testing periods for this system are given in Table 37. Influent flow rates of 21,000 and 10,000 gpd were maintained for the test periods. BOD removal was over 99 percent for the first period but dropped to 95 percent for the second, while ammonia removal was 89 and 99 percent for the same periods. COD removal averaged 95 percent for both. Plant performance was very good during both; but on the average, effluents exceeded discharge limits for BOD, ammonia, cadmium, and lead during one or both periods (Table 37). Costs for operation and maintenance of the plant are shown in Table 38.

Configuration No. 2 included only physical/chemical treatment (actually the first four steps of configuration No. 1). The treatment sequence included equalization, lime addition, sedimentation, and air stripping of ammonia. Leachates were further treated biologically or returned to the landfill. Results of these treatments are shown in Table 39; data are averages over different time periods, so they cannot be directly compared. The data for ammonia stripping also include lime treatment. Lime treatment alone removed 77 percent of the suspended solids, 61 percent of the COD, and 52 percent of the BOD. It also removed 90 percent of the phosphate (which limited further biological treatment). Metal removal was also good, with 53 percent of the magnesium removed; 36 to 39 percent of sodium and potassium; 60 to 70 percent cadmium, chromium, nickel, lead, and mercury; 75 percent of copper; and 97 to 99 percent of the iron and zinc. Further ammonia stripping (lagoon aeration) of the settled, limed leachate removed 50 percent of the ammonia and Kjeldahl nitrogen. Additional losses of dissolved solids, BOD, magnesium, calcium, and chloride reflected additional settling time in the ammonia stripping lagoon or differences in overall leachate concentrations during the different treatment periods. Actual costs of configuration No. 2 treatment are shown in Table 40.

Configuration No. 3 consisted of reversing the biological and physical/chemical stages so that the raw leachates first entered the biological stage followed by lime polishing of the effluent. Configuration No. 4 consisted of the effluent from biological treatment alone. Both these treatment sequences were run after the activated sludge had become acclimated to the leachate. Results consisting of 4-month average values for these configurations are given in Table 41. Biological treatment alone (configuration No. 4) did not meet the discharge standards for ammonia, cadmium, chromium, iron, lead, and zinc, although BOD was significantly reduced. This treatment

[112] R. L. Steiner et al.; B. J. Stoll, "Demonstrating Leachate Treatment," Municipal Solid Waste: Land Disposal, EPA-600/9-79-023a (U.S. Environmental Protection Agency, 1979), pp 313-323.

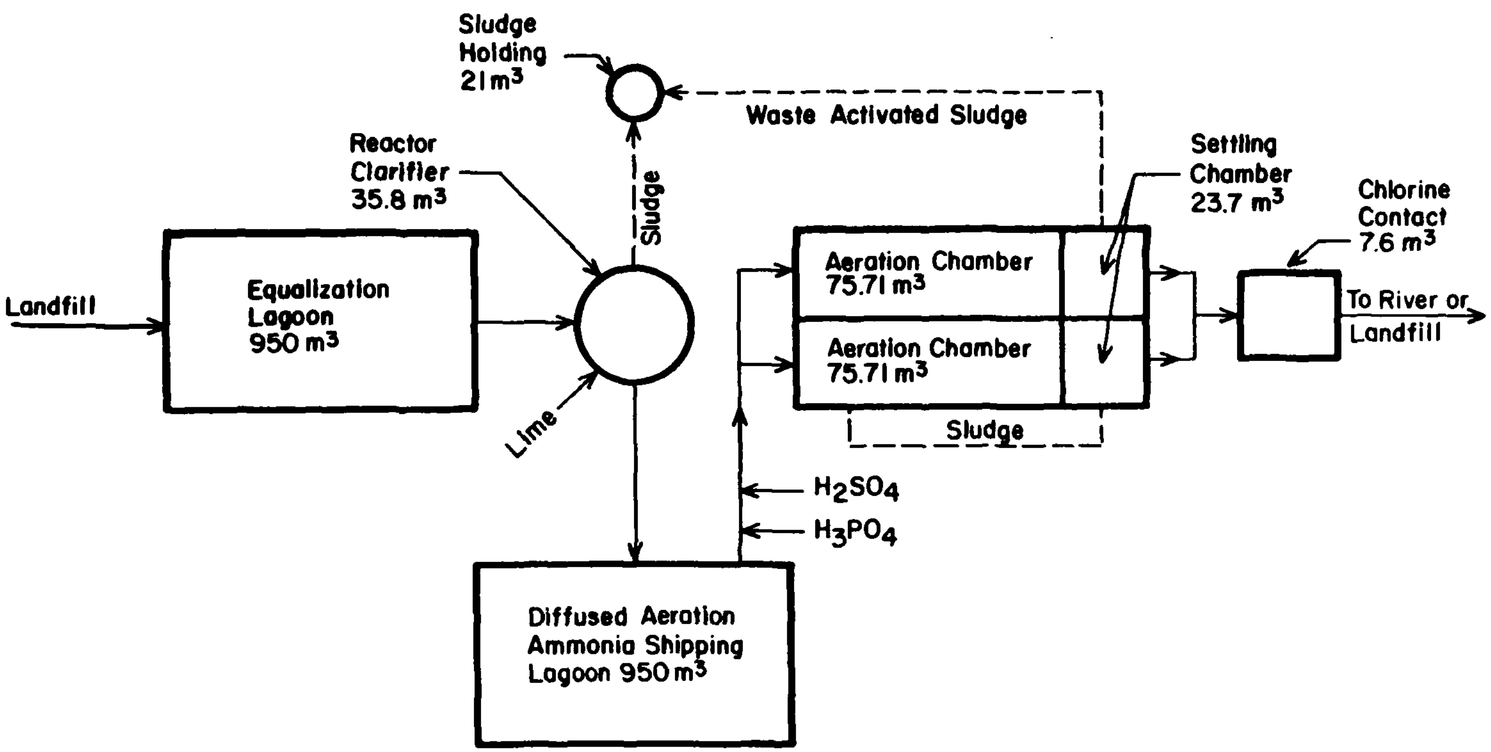


Figure 6. Schematic flow diagram of GROWS leachate treatment plant: Configuration No. 1.

Table 37

Configuration No. 1 -- Treatment Performance After Acclimation of Activated Sludge (Adapted from B. J. Stoll, "Demonstrating Leachate Treatment," in Municipal Solid Water Waste: Land Disposal, EPA-600/9-79-023a [U.S. Environmental Protection Agency, 1979], pp 313-323.)

Parameter	Period of 8/1/76 to 5/1/77			Period of 7/1/78 to 8/31/79			
	Influent, mg/L	Effluent, mg/L	Percent Removal	Influent, mg/L	Effluent, mg/L	Percent Removal	Discharge,* mg/L
Sus. solids	686	101	97.4	1655	478	71.1	--
Dis. solids	13 563	5693	58.0	13 091	7244	44.7	--
COD	18 488	939	94.9	18 505	1008	94.6	--
BOD_5	12 468	118	99.1	8143	464	94.3	100
Alkalinity	5479	685	87.5	5262	1496	71.6	--
Hardness	5331	1314	75.4	2504	1456	41.9	--
Magnesium	499	107	78.6	175	105	62.0	--
Calcium	929	347	62.6	653	113	82.7	--
Chloride	4264	2592	39.2	8578	2254	73.7	--
Sulfate	645	951	--	178	836	--	--
Phosphate	2.15	13.7	--	1.39	17.2	--	--
Ammonia-N	705	80	88.7	1076	6.3	99.4	35
Kjeldahl-N	748	102	86.4	--	--	--	--
Sodium	1310	821	37.3	1248	1145	8.3	--
Potassium	906	524	42.2	872	743	14.8	--
Cadmium	0.08	0.01	87.5	0.06	0.04	33.3	0.02
Chromium	0.28	0.07	75.0	0.16	0.04	75.0	0.1
Copper	0.44	0.10	77.3	0.20	0.16	25.0	0.2
Iron	376	3.0	99.2	9.7	0.71	99.3	7.0
Nickel	1.91	0.76	60.2	0.88	0.67	24.1	--
Lead	0.82	0.12	85.4	0.30	0.11	64.6	0.1
Zinc	22	0.57	97.4	3.38	0.16	95.3	0.6
Mercury	0.006	.004	28.9	0.003	0.002	33.3	0.01
Flow, gpd	21 034			10 000			

* Pennsylvania discharge permit.

Table 38

Operating and Maintenance Costs for Configuration No. 1 During Both Trial Periods
(Adapted from B. J. Stoll, "Demonstrating Leachate Treatment," in Municipal Solid Waste: Land Disposal, EPA-600/9-79-023a [U.S. Environmental Protection Agency, 1979], pp 313-323.)

Component	gal/1000 gal	$/1000 gal
Lime (lb/1000 gal)	36.4	1.10
Sulfuric acid	0.13	0.10
Phosphoric acid	0.019	0.05
Sodium hydroxide	0.123	0.08
Sodium hypochlorite	0.15	0.11
Power	--	1.92
Total Cost	--	3.36

Table 39

Summary of Effects of Configuration No. 2 -- Chemical/Physical Treatment Only

(Adapted from B. J. Stoll, "Demonstrating Leachate Treatment," in Municipal Solid Waste: Land Disposal, EPA-600/9-79-023a [U.S. Environmental Protection Agency, 1979], pp. 313-323.)

Parameter	Leachate Avg. Concentration, mg/L	Lime Treatment Effluent: Avg. Concentration, mg/L	Lime Treatment Effluent: Removal Percent	Ammonia Lagoon Effluent: Avg. Concentration, mg/L	Ammonia Lagoon Effluent: Removal Percent
Sus. solids	1044	239	77.1	288	72.4
Dis. solids	13 029	1972	38.8	4650	64.3
COD	18 553	7188	61.2	8973	52.6
BOD_5	10 907	5265	51.7	3600	67.0
Alkalinity	5404	3052	43.5	2374	56.1
Hardness	4652	2461	47.1	1587	65.9
Magnesium	453	209	53.9	117	74.2
Calcium	818	696	14.9	424	48.2
Chloride	4240	3516	17.1	2669	37.0
Sulfate	462	426	7.8	525	--
Phosphate	2.74	0.26	90.5	0.27	90.1
Ammonia-N	1001	890	11.1	412	58.8
Kjeldahl-N	984	867	11.9	349	64.5
Sodium	1354	830	38.7	956	29.4
Potassium	961	613	36.2	572	40.5
Cadmium	0.086	0.03	65.1	0.04	53.5
Chromium	0.28	0.09	67.8	0.08	71.4
Copper	0.39	0.10	74.7	0.27	30.8
Iron	312	3.8	98.8	5.6	98.2
Nickel	1.55	0.57	63.2	0.73	52.9
Lead	0.67	0.24	64.2	0.23	65.7
Zinc	21	0.61	97.1	0.85	96.0
Mercury	0.007	0.003	57.1	0.010	--

Table 40

Operation and Maintenance Costs of Configuration No. 2
(Adapted from B. J. Stoll, "Leachate Treatment Demonstration," in
Municipal Solid Waste: Land Disposal, EPA-600/9-79-023a
[U.S. Environmental Protection Agency, 1979], pp 313-323.)

Parameter	During Operation Without Equalization Lagoon	During Operation With Equalization Lagoon
Time span, months	8.0	20.5
Flow, average, gpd	22 805	38 618
Lime, lb/1000 gal	29.7	19.40
NaOH, gal/1000 gal	0	0.044
NaOCl, gal/1000 gal	0	0.054
Costs, $/1000 gal		
Power	1.48	1.70
Lime	.89	0.58
NaOH	0	.03
NaOCl	0	.04
Total	2.37	2.35

Table 41

Summary of Effects of Biological Treatment Alone (Configuration No. 4), Followed by Lime Polishing (Configuration No. 3) (Adapted from B. J. Stoll, "Demonstrating Leachate Treatment," in Municipal Solid Waste: Land Disposal, EPA-600/9-79-023a [U.S. Environmental Protection Agency, 1979], pp. 313-323.)

Parameter	Raw Leachate, mg/L	Configuration No. 4 Concentration, mg/L	Configuration No. 4 Removal Percent	Configuration No. 3 Concentration, mg/L	Configuration No. 3 Removal Percent	Discharge Standard
Alkalinity	5087	2788	45.2	1178	76.8	*
Ammonia-N	649	312	51.9	153	76.4	35
BOD_5	12 649	2150	83.0	763	94.0	100
Cadmium	0.11	0.08	27.3	0.02	81.8	0.02
Calcium	937	573	38.8	287	69.4	*
Chloride	4178	3778	9.6	1496	64.2	*
Chromium	0.48	0.37	22.9	0.08	83.3	0.1
COD	21 152	4680	77.9	2257	89.3	*
Copper	0.27	0.22	18.5	.07	74.1	0.2
Disc. solids	14 742	10 081	31.6	5353	63.7	*
Hardness	4463	2805	37.1	914	79.3	*
Iron	348	195	44.0	1.02	99.7	7
Kjeldahl-N	708	347	51.0	180	74.6	*
Lead	0.76	0.50	34.2	0.15	80.3	0.1
Magnesium	350	242	30.9	48	86.3	*
Mercury	0.007	.007	0	.002	71.4	0.01
Nickel	2.0	1.29	35.5	0.27	86.5	*
Phosphates	2.3	4.6	--	0.56	75.7	*
Potassium	1076	996	7.4	476	55.8	*
Sodium	1536	1412	8 1	719	53.2	*
Sulfate	658	853	--	513	22.0	*
Sus. solids	1136	1322	--	180	84.2	*

*No discharge standard for this parameter; others are Pennsylvania discharge permit values.

by lime clarification brought the effluent under discharge standards on the average -- except for ammonia and lead. Detention times in the extended-aeration, activated-sludge reactors during this time were not given; but at design flow, the raw leachate would have had only a 6-hour retention time. If the flow was 25 percent of the design flow during this time, the average detention time would have been about 1 day.

From the results of testing the four treatment configurations, Stoll concludes that "treatment of leachate from this landfill must include biological treatment preceded by chemical/physical processes" to meet discharge standards. Dilution of influent leachate to lower COD and ammonia levels and long detention times were not included in the testing. Stoll recommends a sequence of treatment units like configuration No. 1 to adequately treat landfill leachates to discharge standards. The most significant problem encountered was variability in leachate quantity and quality. The original treatment plant was designed incorrectly; according to Stoll, "the design leachate characteristics...[were] highly inaccurate" because they underestimated constituent levels (especially BOD and ammonia) and overestimated flow rates.

There are two key problems in designing and operating treatment systems. Since the final parameters of leachate flow and quality are not known, the designer must rely upon the literature for "typical" leachate quality; this information must be modified by leachate quality prediction techniques. In addition, variations in leachate quality cause serious difficulty for the operator attempting to automate chemical additions and detention times. Only frequent analysis of the influent leachate and subsequent adjustment of the chemical feed can produce the desired result.

Land Application Experience

At the Mercer County, WV, sanitary landfill, spray irrigation for land disposal of leachate has been used effectively since 1973 to decontaminate the wastewater.[113] Application rates were 0.2 in./hr from sprinklers operating on a pressure of 35 psi for 3 or 6 hours once each week (0.75 and 1.5 in./week). Total application amounts were 14.8 to 60.5 in. for 8 months each year. Organic and elemental pollutants in the leachate declined to generally acceptable levels without affecting soil permeability as water percolated through 23.4 in. of soil. Subsoil acidity was decreased by the addition of calcium and magnesium to the leachates. Manganese concentrations exceeded water quality standards during intense irrigation periods, but fell to acceptable levels during rest periods. Soils retained calcium, magnesium, potassium, iron, and zinc in the surface layer; but sodium, aluminum, and manganese were dispersed throughout the soil profile.

Native deciduous trees and introduced forage grasses generally withstood leachate irrigation, but tended to concentrate materials from the waste. Chlorides increased in most foliage, while elevated concentrations of iron, manganese, sodium, sulfur, and nitrogen were noted in early season growth. Tall fescue and Reed canarygrass contained higher elemental levels than other

---

[113] H. A. Menser, W. M. Winant, and O. L. Bennett, Spray Irrigation; A Land Disposal Practice for Decontaminating Leachates from Sanitary Landfills, ARR-NE-4 (U.S. Department of Agriculture, 1979), 48 pp.

grasses (orchardgrass, bromegrass, and midland and tufcote bermuda). All grasses except bromegrass persisted well. Red maple, yellow poplar (tulip tree), black locust, and sassafras tolerated leachate, but sourwood trees died. Cinquefore, ground pine, and wild strawberry were eliminated by the leachate application and replaced by poison ivy, virginia creeper, and wild blackberry. Lime and phosphate fertilizers aided forage grass establishment. No hazardous levels of potentially toxic heavy metals (copper, chromium, cadmium, lead, or nickel) were found in soils, vegetation, or soil percolates. Noxious odor control and waste stabilization were important benefits of leachate aeration.

Land application of landfill leachate has been used extensively in Cornwall County, England.[114] Table 42 gives details about four sites. All land application installations provide efficient, cheap treatment and disposal of leachate. They operate continuously through widely varying flow rates with minimum maintenance and supervision. In land irrigation, maximum dosage rates depend on rainfall patterns, and land and soil types. In areas with 45 in. of rain per year -- such as Cornwall -- dosage rates under the most adverse conditions of 3000 gal/acre can be used; at an average site, dosages of 5000 gal/acre are not unreasonable. According to Rowe, leachate strength is of only minor importance; leachate with BOD values over 500 mg/L can be directly applied to land. Oxides of iron stain vegetation but seem to have no serious effect on plant life. Plant diseases and scorching of foliage have not been excessive nor harmful.

Lagoon Treatment of Leachates: Field Experience

One of the landfill leachate treatment systems studied most often is the Martone Landfill in Barre, MA (Figure 7). This small landfill (150 tons of refuse per week) was designed and built in cooperation with the University of Massachusetts. It has a clay liner and leachate collection system specifically for the study of leachate production and treatment. The system uses aerobic lagoons which are 1.6-ft deep and are built at the toe of the landfill, as shown in Figure 8. The leachate is now kept in one of four lined ponds for a 90-day retention time. After this, the treated leachate is drained into a larger aerobic polishing pond and into an unlined infiltration pond from which it percolates into the soil. During several years of operation and testing with the 90-day retention time, the system has maintained about 99 percent treatment efficiency for BOD, COD, nutrients, and most metals. This treatment system has proved to be a workable and reliable operation which requires low capital investment, relatively small land area, and low operating and maintenance labor costs (although periodic water quality analyses are still required).

A similar system has now been built at a 30-acre active municipal landfill in Lowell, MA. The leachate is collected in a lined lagoon at the toe of the landfill. Natural drainage is used to collect and convey the leachate. The collection lagoon has three mechanical surface aerators (Figure 9). Effluent from this lagoon is pumped into one of six facultative ponds around

---

[114] V. C. Ultoth and D. S. Mavinic, "Aerobic Bio-Treatment of High-Strength Leachate," Journal of Environmental Engineer Division, Proceedings, American Society of Civil Engineers, Vol 102, EE4 (1977), pp 647-661.

Table 42

Details of Land Treatment Facilities at Four British Landfills (Adapted from A. Rowe, "Tip Leachate Treatment by Land Irrigation," Solid Wastes, Vol 69, No. 12 [1979], pp 603-623.)

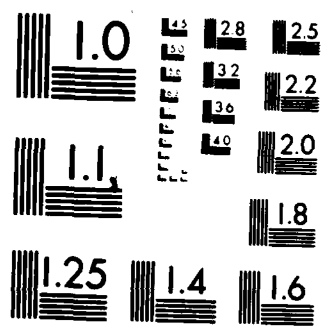
	Trezise	Conce Moor	Connon Bridge	Treworder
Irrigation area	5 acres	6 acres	2-1/2 acres	
Landfill area	27 acres	30 acres	--	--
Normal expected winter leachate flow	10,000-20,000 gpd	30,000-50,000 gpd	10,000-50,000 gpd	20,000-30,000 gpd
Leachate BOD, mg/L	Up to 5500	150-1250	108-810	
Pump	20 hp, three phase centrifugal, 2900 rpm, approx. 5000 gph at 180-ft head	(Same as Trezise)	(Same as Trezise)	Temporarily on fire engine pump. To be installed: three phase, approx. 5000 gph at 180-ft head
Delivery pipeline	3-in PVC anger joint and 3-in aluminum high-speed coupling pipe	4- and 3-in. PVC anger joint to 3-in aluminum high-speed coupling pipe	3-in. PVC anger joint supplying leachate	3-in PVC anger joint pipe
Distribution method	Standard angle sprinkler (1/4-in. nozzle)	Standard angle sprinkler (1/4-in. nozzle)	75-mm-diameter slotted irrigation pipelines 50-ft apart and 60-ft long. Each length supplied through separate control valve for balanced flow.	50-mm-diameter slotted pipeline in 60-ft lengths distributing leachate over strip 30-ft wide; controlled as at Connon Bridge.
Installation cost (excluding land)	$7950	$11,600	$13,330	$14,400
Electric power	$8600	$7525	$12,400	$10,750

AD-A132 483 TREATMENT OF LANDFILL LEACHATE AT ARMY FACILITIES(U) CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAIGN IL R A SHAFER ET AL. AUG 83 CERL-TR-N-155

2/2

UNCLASSIFIED F/G 13/2 NL

END
DATE
FILMED
10 83
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

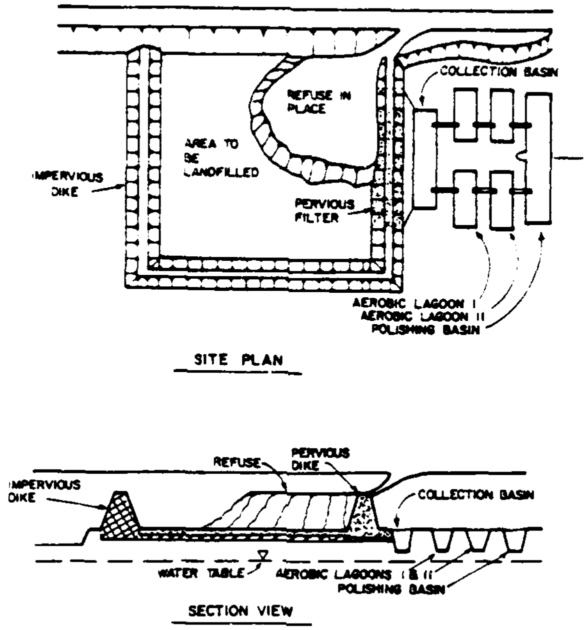


Figure 7. Schematic diagram of Martone aerobic lagoon treatment system for landfill leachate.

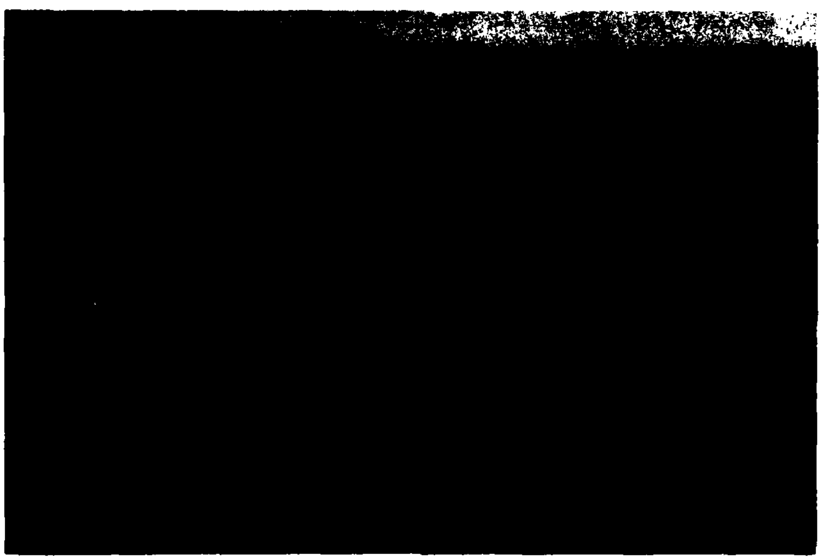


Figure 8. Aerobic leachate treatment lagoons at the Martone landfill. (The landfill is above the lagoons to the right. The longer pond to the left is a polishing pond where the leachates are combined after 90 days in one of the four treatment ponds.)

the landfill. These ponds have a 90-day retention time (Figure 10). The effluent from the ponds is then pumped either to an infiltration pond or a city storm sewer (depending on effluent quality).

Extensive testing of lagoon treatment of leachates from simulated landfill cells has been carried out by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) in Vicksburg, MS. The treatment system basically consists of a series of three shallow (1.4-ft) lagoons having a 30-day hydraulic retention time per cell and a 90-day retention overall. Two such systems are run in parallel -- one with supplementary aeration during the night, and the other without aeration.

The lagoons were seeded with aerobic sludge from the secondary clarifier of the local treatment plant. The system was acclimated to leachate by adding the effluent at 10 percent of the design organic load, and increasing this load by 10 percent each day until 100 percent loading was reached. Design loading was 50 lb BOD/acre/day. Hydraulic loading was 13,700 gal/acre/day (438 mg/L BOD); extra makeup water to dilute the leachate was drawn from a local creek. The amount of dilution necessary to maintain the design loadings was calculated from daily COD determinations; weekly BOD values were used to adjust the BOD/COD ratio. COD values in the feedstock varied between 2500 mg/L and 17 500 mg/L, averaging 5600 mg/L. BOD values varied between about 2000 and 12 500 mg/L, averaging 3970 mg/L. Mean BOD/COD ratio in feed leachate was 0.71. The raw leachate feed was typically diluted 3 to 10 times its volume with creek water, depending on the leachate's BOD level.

Table 43 shows the mean oxygen demand levels of the effluents from the six lagoons over the 118-day experimental period. COD was lowered to about 86 percent of its influent level in the aerated lagoon series, and to 89 percent in the nonaerated series. BOD treatment efficiencies averaged about 97 percent for both lagoon series. Ammonia levels in the leachate were lowered by more than 99.5 percent in both cases. The weekly mean values of BOD removal efficiency for the two lagoon series are shown in Figures 11 and 12.

The capability of the first lagoon in each series to remove BOD varies widely between 70 and 95 percent. The second lagoons are much more consistent in both series; but the third lagoon produces the most consistent effluent quality -- between 97 and 99 percent removal.

There was a major upset in both lagoon series around day 90. The cause is thought to be either a change in leachate source or major rainfall which occurred at about this time. In both systems, the BOD removal from the first two lagoons dropped rapidly; at the end of the upset period, the effect of this was shown in the effluent from the third lagoon of the aerated series. Both systems recovered rapidly and were back to high treatment efficiencies within a few days.

Table 44 gives other parameters from the two lagoons. Oxygen depletion would be expected, but none was shown in the lagoons of the aerated series. Oxygen levels in the first nonaerated lagoon dropped dramatically at night at 6-in. depth and even remained low throughout the day at 18 in. The second and third lagoon in the nonaerated series had normal oxygen levels similar to those in the aerated lagoons. Algal populations were very high in the first lagoons and dropped dramatically through both systems. The kinds and number

Figure 9. Aerated treatment lagoon at Lowell, MA landfill. (In the foreground, note pattern of bubbles from one of the three mechanical aerators.)

Figure 10. Facultative treatment pond to which effluent from aerated lagoon is pumped at Lowell, MA. (Note heavy vegetation; pond shows intense biological activity.)

Table 43

Mean Oxygen Demand and Ammonia Levels of the Lagoon Effluents Over the 118-Day Experiment

	Hydraulic Retention Time, Days	Effluent COD, mg/L	COD Treatment Efficiency, Percent	Effluent BOD mg/L	BOD Treatment Efficiency, Percent	BOD/COD	NH_3 mg/L
Aerated Lagoon							
First	30	181	71.0	72	83.5	0.40	25.7
Second	30	135	78.2	44	89.8	0.32	0.34
Third	30	87	85.9	14	96.6	0.16	0.05
Nonaerated Lagoon							
First	30	152	75.4	83	80.9	0.54	10.5
Second	30	118	81.0	30	93.0	0.25	0.55
Third	30	69	88.9	11	97.5	0.16	0.20

Note: Treatment efficiences based on influent values of BOD equal to 438 mg/L, COD equal to 617 mg/L, and ammonia 40.1 mg/L.

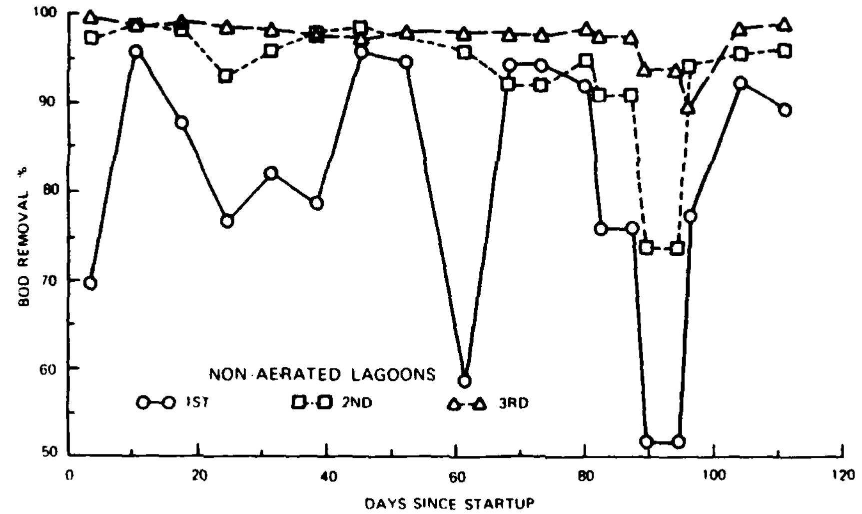


Figure 11. BOD removal efficiencies for nonaerated series of leachate treatment lagoons over length of study at WES.

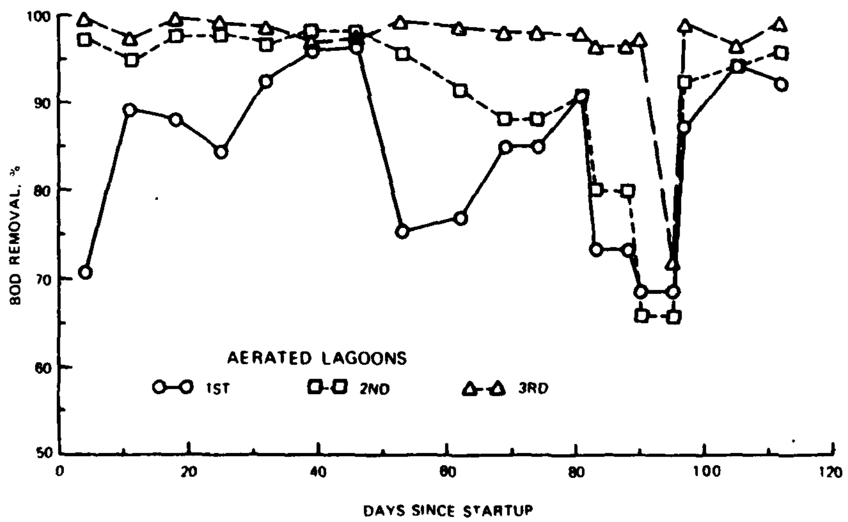


Figure 12. BOD removal efficiencies for aerated series of leachate treatment lagoons over length of study at WES.

Table 44

Average of Selected Parameters for Both Aerated and Nonaerated Lagoon Series

	Mean Temperature, °F				Mean Dissolved Oxygen, mg/L				Mean pH, 6-in. depth at 0630	Mean Algal Concentration, cells/ml
	6-in. depth		18-in. depth		6-in. depth		18-in. depth			
	0630	1300	0630	1300	0630	1300	0630	1300		
Aerated Lagoons										
First	76.3	85.8	85.9	80.8	5.87	14.8	5.23	4.25	8.2	20,350
Second	77	86.4	76.8	82.4	6.57	14.5	5.96	10.3	8.9	7980
Third	76.6	85.8	76.3	83.7	6.73	10.1	6.31	10.7	8.4	210
Nonaerated Lagoons										
First	76.1	85.1	85.9	80.4	2.02	9.83	1.35	2.35	8.2	16,060
Second	76.8	85.8	76.6	81.9	6.76	14.2	6.15	10.9	8.9	4165
Third	76.3	84.9	85.9	83.5	7.05	10.1	6.66	10.5	8.5	310

of algae present varied widely from day to day, often producing a surface blanket on the first and sometimes on the second lagoons (Figure 13).

There is a striking reduction of COD when the raw leachate is stored in a closed but vented cluster-tank (seen in right background of Figure 13). Figure 14 shows that the COD rapidly decays with a half time of 5 to 7 days. This effect is thought to be caused by the loss of small, volatile organics, and/or the oxidation of ferrous to ferric iron by atmospheric oxygen. Considerable "treatment" can occur simply in a holding tank.

The arrangement of three lagoons in series with extended hydraulic retention times is successfully treating high-strength landfill leachate at WES. The BOD loading of the shallow lagoons is kept at 50 lb/acre/day with a constant hydraulic loading by dilution of the leachate with makeup water from a local creek. Earlier tests with 100 lb/acre/day BOD loading with the same

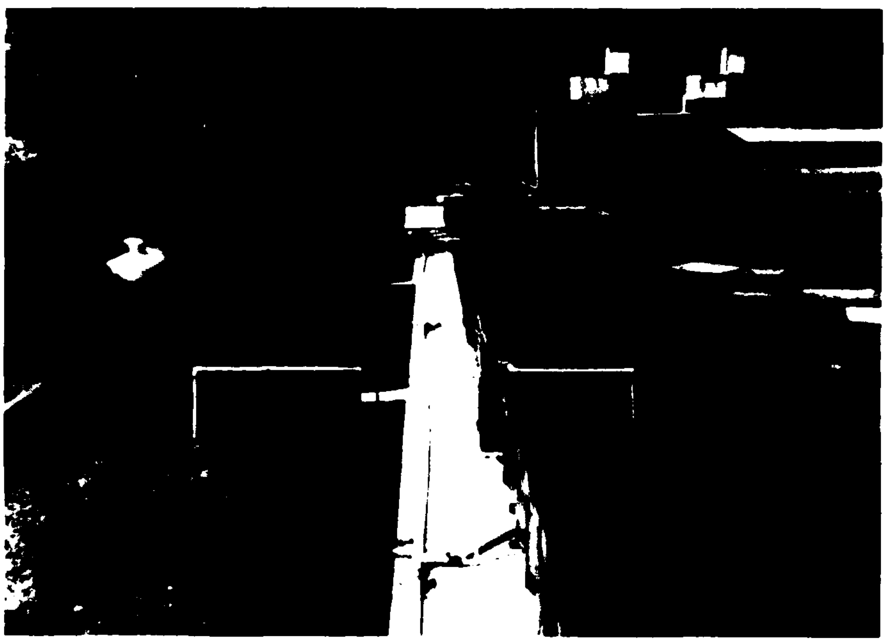


Figure 13. Leachate study facilities at WES. (Aerated lagoons are on right, nonaerated on left. Note cluster tank for leachate storage in right background.)

hydraulic loading caused instability and frequent break-through. Deeper lagoons should allow higher organic loading without instability.

Another variation of an aerobic lagoon system is being operated at Lycoming, PA. The Lycoming landfill accepts municipal solid waste with about 30 percent industrial wastes. It is equipped with a 20-mil PVC membrane liner and has a leachate collection system designed with 6- to 8-in. perforated pipes installed in gravel above the liner. The leachate drains are interconnected with vertical pipes which act as gas vents to prevent buildup of methane in the fill. The gas vents are enclosed in vented conduit. The leachate treatment system consists of a lined lagoon with two mechanical surface aerators, as shown in Figure 15. Leachate treated in this lagoon is recirculated back to the working face of the landfill and pumped into 15-ft-deep trenches dug through the compacted refuse (Figure 16). The leachate has high metals load because of the large amount of industrial waste accepted and the recycling of the leachate back into the landfill. The high metals levels and toxicity of the leachate inhibit most of the biological activity; so aeration mainly purges volatile organics and destroys the more easily oxidized components, such as odorous sulfur compounds. The retention time in the collection pond is usually 1 to 2 days. Because new refuse is constantly added to absorb the recycled effluent, there is no leachate discharge. However, if leachate must be discharged, more extensive treatment may be required.

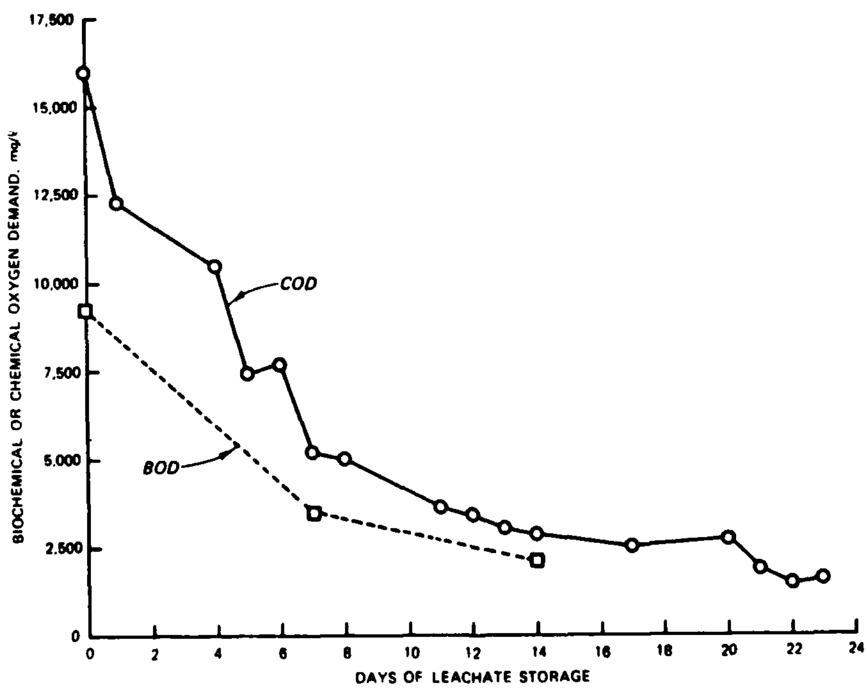


Figure 14. BOD and COD levels in closed, vented storage tank (491 gal) over 3 weeks.

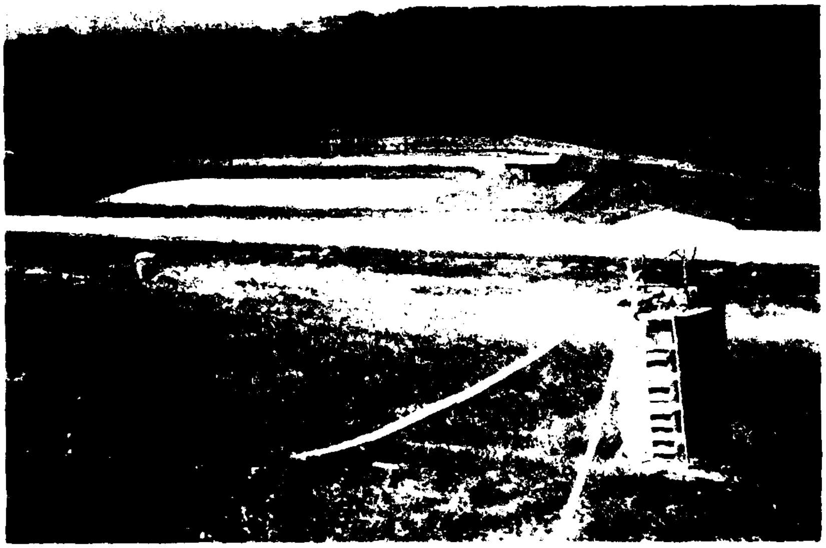


Figure 15. Aerated collector pond at Lycoming, PA. (Note gas vents in foreground.)

Figure 16. Backhoe digging trench through refuse for leachate recycle at Lycoming, PA, landfill. Leachate recycled directly into trenches.

5 CHOOSING A TREATMENT SYSTEM

The composition and biodegradability of leachates varies widely, depending on waste types and densities, and landfill ages. Therefore, no single treatment option or combination of options can be recommended for all circumstances. Selection of the best treatment process requires knowledge of the quality and quantity of leachate to be treated and the specific discharge requirements of the site. Treatment systems currently adequate may become unsatisfactory because of regulatory revisions or changes in leachate composition during aging of the landfill. Fluctuations in leachate quality and strength can make it difficult to maintain an active biomass for biological treatment or to automate chemical treatment systems.

Biological Treatment Systems

Treatment systems relying on biological activity are most effective when used on leachates from recently placed refuse, where most of the organic carbon is in the form of volatile fatty-acids. However, biological methods do not remove as effectively, the smaller content of fulvic acid-like materials (and to a lesser extent the humic carbohydrate-like substances) which make up the rest of the leachate. This means that the less concentrated leachates from older landfills, and the residuals from biological treatment of young leachates, are better treated by physical/chemical methods. The combination of biological and physical/chemical treatment methods most suitable in any given circumstance must be determined. To do this, one should estimate the degree of *stabilization (or age)* of the landfill by determining the COD and BOD levels of the leachates and comparing the absolute COD levels and the BOD/COD ratio with the values given in the leachate composition summary in Chapter 2. Active organisms can be seriously inhibited and frequent treatment breakdown can be caused by toxic organics and heavy metals. Therefore, they should be identified in leachates being considered for biological treatment.

Aerobic and anaerobic systems have been given extensive bench-scale study; both effectively remove organics and other constituents from landfill leachates.[115] Table 45 summarizes treatment processes and their removal efficiencies. In all cases, good removal efficiencies are seen with residence time over 10 days. Full-scale treatment systems have almost exclusively used aerobic conditions. In general, conventional activated sludge systems do not work as well with high-strength leachates; therefore, dilution with clean water or plant effluent at the site is a requirement. The activated sludge systems studied require retention times longer than 5 days to prevent system

---

[115] Estimating Waste Treatment Costs, Vol 3; E. N. Cook and E. G. Foree; E. S. K. Chian and F. B. DeWalle, Vol I; E. S. K. Chian and F. B. DeWalle, Vol II; V. C. Ultoth and D. S. Mavinic; T. Palit and S. R. Qasim, "Biological Treatment Kinetics of Landfill Leachate," Journal of Environmental Engineer Division, Proceedings of the American Society of Civil Engineers, Vol 103, EE2 (1977), pp 353-366; R. Zapf-Gilje and D. S. Mavinic, "Temperature Effects on Two-Stage Biotreatment of Leachate," Proceedings of American Society of Civil Engineers, Environmental Engineer Division, Specialty Conference on Environmental Engineering (1979), 825 pp; R. Stegmann and H. J. Ehrig.

Table 45

Summary of Removal Efficiencies of Bench-Scale Biological Treatment Processes

Process	Leachate COD, mg/L	Solids Residence Time, Days	Removal Efficiency, Percent	References
Activated sludge	2700	5	80 to 93	Boyle and Ham, 1974
	360	9	88.2	Palit and Qasim, 1977
	19 000	15	97.8	Graham and Mavinic, 1979
	19 000	25	98.1	Graham and Mavinic, 1979
Anaerobic sludge	10 600	10	93.4	Boyle and Ham, 1974
	10 600	12.5	94.5	Boyle and Ham, 1974
	13 000	10	92	Foree and Reid, 1973
	13 000	20	93 to 95	Foree and Reid, 1973
	27 000	10	90	Chian and DeWalle, 1977
	27 000	10	90	Chian and DeWalle, 1977
Aerobic completely mixed	35 000	7*	97.1	Chian and DeWalle, 1977
	35 000	15*	97.8	Chian and DeWalle, 1977
	35 000	30*	98.5	Chian and DeWalle, 1977
	15 800	5*	46.5	Cook and Foree, 1974
	15 800	10*	97.7	Cook and Foree, 1974
Facultative lagoon	--	90*	95 to 99	WES lagoon study described in Chapter 4

*Hydrologic retention time.

failure and to develop maximum removal efficiencies. The only large-scale anaerobic leachate system now under study in the United States has not been effective because of the low level of biodegradable organic materials in the feed.[116]

Landfill leachate is sometimes nutrient-limiting in phosphorus, so phosphate additions are often recommended to increase system efficiency and reduce retention times.[117] Heavy metal toxicity has been a possible problem in only one system studied.[118] But lime and sulfide additions as a pretreatment have been included in several studies to remove metals.[119]

[116] M. P. Scott.
[117] E. S. K. Chian and F. B. DeWalle, Vol II; B. J. Stoll.
[118] E. S. K. Chian and F. B. DeWalle, Vol II.
[119] E. N. Cook and E. G. Foree.

Applying raw or semitreated leachates to natural or prepared soils by irrigation techniques is gaining wide acceptability.[120] Land application effectively promotes evaporative losses, removes organics by microbial degradation, and removes inorganics by precipitation or ion exchange on the soil. Many of the nutrient materials are rapidly taken up by vegetation. With some conditions, year-round land application may not be feasible, and a storage lagoon may be required. Spraying or irrigation is done only during dry periods when the temperature is above freezing. Both woodlands and grassland sites with soil ranging from peat to sandy to clayey have been used successfully for as long as 4 years with no apparent harmful effects or toxic accumulations. The major long-term problems anticipated are metal buildup in the soil and the loss of contaminants to groundwater or surface waters at the site.

Leachate recycle can be considered a specialized case of land treatment in which the area being used for leachate application is the landfill itself. This greatly lessens the potential for contaminating new areas and guarantees that the microflora of the soil and refuse are already acclimated to the leachate's properties. Pohland has suggested a recycling management technique in which the properties of the leachate are adjusted before the effluent is sprayed or pumped back into the landfill.[121] By adjusting leachate pH values or nutrient levels, one can improve the biological activities occurring in the fill, such as methane production or degradation of organics. Pilot-scale tests have indicated that leachate recycling greatly accelerates landfill stabilization and can shorten the time that leachate treatment may be necessary.[122]

Physical/Chemical Treatment Systems

Treatment processes using physical or chemical operations have also been applied experimentally or suggested for leachate treatment; several have been used in bench-scale studies of leachate treatment. Carbon absorption or reverse osmosis appear promising for removal of refractory organics. Chemical precipitation, ion exchange, or reverse osmosis may be used best for metal and total dissolved solids removal. Lime addition in the final treatment stage reduces residual organics and metals in activated sludge effluent, but the

---

[120] H. A. Menser, W. M. Winant, and O. L. Bennett, 1979; H. A. Menser et al., "The Utilization of Forage Grasses for Decontamination of Spray-Irrigated Leachate from a Municipal Landfill," Environmental Pollution, Vol 19 (1979), pp 249-260; H. D. Robinson, and P. J. Marris, Leachate From Domestic Waste: Generation, Composition, and Treatment -- A Review, TR-108 (U.K. Water Research Center, 1979), p 38; A. Rowe, "Tip Leachate Treatment by Land Irrigation," Solid Wastes, Vol 69, No. 12 (1979), pp. 603-623.

[121] F. G. Pohland, Sanitary Landfill Stabilization With Leachate Recycle and Residual Treatment, EPA-600/2-75-043 (U.S. Environmental Protection Agency, 1975), 116 pp; F. G. Pohland, "Leachate Recycle at Landfill Management Option," Journal of Environmental Engineering, Proceedings of the American Society of Civil Engineers, Vol 106, EE6 (1980), pp 1057-1069.

[122] F. G. Pohland, 1980.

lime dosages are so large that they are uneconomical.[123] Effluent polishing by carbon absorption is also effective and may be more economical.[124]

Several reports on the use of a variety of physical/chemical treatment systems on high-COD leachates have concluded that none is feasible unless preceded by biological treatment which reduces the COD.[125] Chemical oxidation -- using chlorine, hypochlorite, permanganate -- and ozone were not more effective, and all required prohibitively expensive doses of oxidant for treating leachates. Reverse osmosis is initially effective but is plagued by membrane fouling and loss of flow. Adsorption by activated carbon appears to be most effective, but is still unsatisfactory on raw leachates because of the very high levels of organics and fouling of the columns.

Estimating Leachate Treatment Costs

Chian and DeWalle summarize cost estimates for treating leachates at two BOD_5 levels and flow rates.[126] Details about calculating the cost estimates are given in the appendix. To estimate the cost of treating combined leachate and activated sludge, fixed costs of \$2/1000 gal and \$6/1000 gal of leachate were added for transporting leachate at flow rates of 20 gpm (30,000 gpd) and 2 gpm (3000 gpd), respectively. The \$2/1000 gal value is for transporting leachate by pipeline, while the 1000 gal figure is for auling it by trucks within a radius of 15 mi (i.e., 30-mi round trip). To transport leachate at a flow rate of 2 gpm by pipeline would cost around \$15/1000 gal even if the pipeline is depreciated over a 20-year period. It should be realized that the use of a 20-year period to depreciate fixed installations may not be realistic since the strength of the leachate produced would be reduced greatly over such a time.

It can be seen from Table 46 that the aerated lagoon provides the least expensive method of treating leachate having a comparatively low BOD_5 value (e.g., 5000 mg/L) and relatively high flow rate (e.g., 20 gpm). At a 20-gpm flow rate, as the BOD_5 level of the leachate increases, the cost of treatment with anaerobic filters becomes increasingly attractive; at a BOD_5 value of 25,000 mg/L, the cost equals that of the aerated lagoon process if credit for the methane gas produced (e.g., at \$1.50/1000 cu ft) is deducted. Taking into consideration the treatment level and thus the effluent quality, the combined treatment of leachate using the activated sludge process becomes most desirable because of the high dilution factor -- especially when the leachate BOD_5 levels are low and the flow rates high.

It should be noted that at high leachate BOD_5 levels (i.e., 25 000 mg/L), and at both flow rates under study, the costs of complete leachate treatment using aerated lagoons and physical/chemical processes (such as a combination of slow sand filtration, activated carbon adsorption, and reverse osmosis) are comparable to those for combined treatment of leachate and domestic or municipal wastewater by activated sludge. The effluent quality is, however, far

[123] D. W. Graham and D. S. Mavinic.
[124] E. N. Cook and E. G. Foree.
[125] S. Ho, W. C. Boyle, and R. K. Ham; E. S. K. Chian and F. B. DeWalle, D. W. Graham and D. S. Mavinic.
[126] E. S. K. Chian and F. B. DeWalle, Vol II.

Table 46

A Summary of Cost Estimates for Leachate Treatment

Treatment Process	Leachate, gal/min	Typical Effluent COD, mg/L at an Influent BOD of 25 000 mg/L	Typical Effluent COD, mg/L at an Influent BOD of 5000 mg/L	Costs of Treatment at an Influent BOD of 25 000 mg/L	Costs of Treatment at an Influent BOD of 5000 mg/L
Activated sludge (AS)	20	30	30	23.6	6.0
(combined)	2	30	30	41.4	11.9
Aerated lagoon (AL)	20	500	100	17.9	4.1
	2	500	100	31.6	10.0
Anaerobic filter (AF)	20	1500	300	22.1(17.9)*	6.8(5.9)
	2	1500	300	43(38.8)	17.7(16.8)
AL-sand filter (SF)	20	125	25	25.7	7.3
-activated carbon (AC)	2	125	25	39.9	13.7
AL-SL-AC-reverse	20	25	5	27.6	9.2
osmosis (RO)**	2	25	5	44.6	18.4
AF-SF-AC	20	375	75	32.8(28.6)	10.6(9.7)
	2	375	75	54.2(50)	22.0(21.1)
AF-SF-AC-RO**	20	75	15	34.7(30.4)	12.5(11.5)
	2	75	15	58.9(54.3)	26.7(25.4)

*Numbers shown in parentheses indicate the costs of treatment after deducting the credit for methane produced at $150/1000 cu ft.

**After RO treatment, the total dissolved solids decreased to 300 mg/L and 60 mg/L for influent leachate BOD concentrations of 25 000 mg/L and 5000 mg/L, respectively.

better when the complete treatment scheme is used. With the combined municipal wastewater/leachate treatment process, the BODs are 5 and 30 mg/L, respectively, for the effluent produced by the complete treatment system. The total dissolved solids levels are 300 and 750 mg/L, respectively. In addition, the color-bearing materials are removed completely with the complete leachate treatment process. Therefore, to lessen the impact of the treated leachate on the environment, complete treatment using aerated lagoons and physical/ chemical treatment processes is most desirable. As leachate BOD_5 levels decrease, however, the difference in treatment costs between complete leachate and a combined municipal wastewater/leachate system would be somewhat greater.

Although the information presented in Table 46 can be particularly valuable in establishing the effect of changes in leachate flow rates and BOD_5 levels on treatment costs, the specific costs presented should be used with caution. It should be realized that specific circumstances may alter treatment costs drastically. For example, if the leachate were allowed to discharge into a municipal wastewater treatment plant having excess capacity, the cost (in terms of the surcharges paid) could be substantially lower than the estimates presented here.

Lagoon Treatment of Landfill Leachates -- Design Guidance

This cost analysis suggests that a lagoon system often is the most economical alternative for treating low volumes of young sanitary landfill leachate. The advantages of these systems are their low initial investment requirement and low operation and maintenance costs, their extreme simplicity of operation and lack of sludge handling requirements, and their capacity to withstand hydraulic and organic shock loadings. However, unless very long hydraulic detention times are used, effluent quality often does not meet secondary standards because of the suspended solids from algal production. BOD and nutrient removal efficiencies drop quickly and must be monitored before discharge.

The primary lagoon systems applicable in leachate treatment are aerobic and facultative. Design data for sewage treatment facilities are used as a best approximation since leachate treatment parameters have not been established. WES's experience with pilot-scale lagoons indicates that the treatment of leachate may be expected to differ from municipal sewage treatments in that a large fraction of the BOD consists of volatile organic acids which are rapidly lost to the atmosphere; BOD's may drop from 50 000 mg/L to 5000 mg/L in 12 to 48 hours in a shallow pond. The large volatile component makes loading factors difficult to use as design criteria. A second difference in leachates is the large proportion of the COD which is represented by ferrous iron. The oxidation of ferrous to ferric iron by bacteria spontaneously causes oxygenation problems. In addition, a large amount of ferric hydroxide precipitate is generated; this clogs filters and causes sludge buildup. Depending on the composition of the waste in the landfill, toxic levels of heavy metals and special organics can be present in the leachates -- just as they might be in the influent of sewage treatment plants which have industrial customers. Heavy metals have been a problem only when there was substantial recirculation of leachate.

Landfill leachates also differ from sewage in that the flow volume and content can vary considerably, depending on temperature and precipitation. In most areas, maximum leachate production occurs in the spring and falls to very low flows in the summer and fall -- except after heavy rain. Frozen landfills generally produce little or no leachate. Lagoon systems should be designed to handle the highest seasonal flow. Outflow may have to be stopped during a low flow season, or water may have to be pumped in from an external source to maintain appropriate treatment depths. Retention times may also be quite variable. Because of these difficulties, the design parameters given here should be considered only very broad estimates.

Before a specific leachate treatment system can be designed, as much background information as possible should be collected. In many areas where leachate treatment becomes necessary, much of the basic data will not readily be available, and sound engineering judgment will be needed. For example, seasonal leachate flow volumes, anticipated COD and BOD loads, solids content, and seasonal temperatures and radiation may have to be estimated. The following list of information requirements includes most important parameters; the specific items in parentheses are particularly important.[127]

1. Waste type and characteristics:

   a. Domestic (type, age, compaction)

   b. Industrial (type, age, pretreatment)

   c. Combination (relative percentages)

2. Leachate characteristics:

   a. Volume (minimum, maximum, seasonal averages)

   b. Concentration of organics (COD, BOD, TOC)

   c. Solids (total, settleable, suspended, dissolved, total volatile, and fixed solids)

   d. Nutrient concentration (nitrogen, phosphorus)

   e. Toxicity (BOD reduction rates, bioassays, pathogens)

   f. pH (minimum, average, maximum, buffering capacity)

3. Site hydrology and meteorology:

   a. Evaporation (average, seasonal)

   b. Rainfall (average, seasonal, major storms)

   c. Air and water temperature (average, seasonal, hottest month, coldest month)

---

[127] E. F. Gloyna.

d. Groundwater (average depth, permeability of formation)

e. Wind (average seasonal velocities and directions)

f. Cloud cover (seasonal averages)

g. Solar radiation (minimum monthly, seasonal, and annual average)

4. Topography:

a. Soil characteristics (ease of excavation, embankment use, percolation, compaction)

b. Flood stages (100-year flood, high-water marks)

c. Local housing, industry (distance to residential and commercial areas)

d. Surface flow (stream, seasonal flow)

5. Use of effluent:

a. Groundwater supplementation

b. Immediate irrigation

c. Industrial use

d. Wildlife or recreational use.

Lagoon treatment of landfill leachate presents unusual design problems:

1. The strength of leachate varies with time and with the nature of the waste in the landfill.

2. Flow rates are determined largely by rainfall and infiltration.

3. Major treatment may have to continue after the landfill has stopped receiving refuse and has been closed.

Fortunately, the design and operation of lagoon systems and adaptations of lagoon systems can be very flexible. And since lagooning has low operations and maintenance costs, it can be continued economically after landfill closure.

Most lagoon treatment systems for landfill leachate designs have followed guidance for conventional sewage lagoons.[128] In addition, however, landfills must be designed to accommodate changes in the strength and volume of leachate. Strength changes can be handled by varying retention times or diluting the effluent with treated water. The volume of leachate can be controlled with modular lagoons and with equalization using the landfill itself (by recycling excess leachate during high flow periods) or equalization

[128] R. L. Culp et al; M. J. Hammer; Metcalf and Eddy, Inc.

lagoons. Provisions can also be made for adding intermittent chemical treatment or nutrient supplementation for biological treatment.

Lagoon design usually begins with an estimate of leachate volume based on rainfall, assumed infiltration rate, and liner leakage. The work of Fenn, and Perrier and Gibson can be helpful in developing estimates of average and maximum leachate flow.[129] In most cases, the lagoon and recycle or equalization system should be designed to handle the 25-year maximum.

Leachate strength and specific treatment problems related to a particular landfill are usually determined by checking existing leachate samples from landfills accepting the same refuse. Treatability studies on a bench scale are very helpful.

Discharge systems, such as spray irrigation or overland flow, often can be established to provide a polishing system or to limit the effects of treatment system failure. Excess lagoon capacity that allows operation with intermittent discharge is often useful because lagoon operators can ensure that the water's quality is acceptable before release. Where appropriate, treated leachate can be discharged into municipal sewage systems to allow further treatment and dilution.

Treatment systems can also be designed to promote stabilization of the landfill by adding water to the refuse or retaining water in the refuse to make sure there is as much bacterial action as possible. Gas production can be increased by leachate recycling. Accelerated stabilization of a landfill can decrease the time needed for leachate treatment and return of the land to other uses.

Design Example for a Single Aerated/Facultative Lagoon

The following example of system design is for a facultative lagoon to which aeration may be added to increase the loading. The contents of a facultative lagoon are not completely mixed (even with aeration), so portions of the incoming and biologically produced solids settle to the pond's bottom zone, which is anaerabic. The anaerobic decomposition in the bottom layer promotes a more complete breakdown of the wastes and a higher quality effluent than does a strictly aerobic (completely mixed or very shallow) lagoon. The aerobic upper zone aids in the rapid metabolism of dissolved components, and in the oxidation and destruction of any reduced material (such as sulfides) which may be released from the anaerobic lower layer. An evaporative/facultative lagoon may also be useful in warm or arid regions where total retention is necessary.

Design Input Data

1. Leachate flow data. This parameter is difficult to estimate with the current understanding of and experience with landfills. Flow depends on parameters such as rainfall, infiltration rate, landfill cover, liner configuration, and leakage to groundwater. The work of Fenn et al., and of Perrier and Gibson can be helpful in developing estimates of average and seasonal

[129] D. G. Fenn et al.; E. R. Perrier and A. C. Gibson.

maximum flow rates.[130] It is suggested that the leachate lagoon, recycle, or equalization system be designed to handle the 25-year maximum expected flow.

2. Leachate characteristics. These are also difficult to estimate and are usually quite variable with the season and the age of landfill:

a. BOD level (mg/L) -- may also be inferred from COD levels and age of landfill.[131]

b. SS (mg/L) -- usually not a problem in leachate influent unless oxidation of ferrous iron has occurred.

c. VSS (mg/L) -- this fraction is the portion of the suspended solids which will volatilize at 1112°F.

d. Nitrogen (mg N/L).

e. Phosphorus (mg/L).

3. Desired degree of treatment. This is usually stated in terms of effluent standards such as secondary treatment standards of SS; BOD monthly and weekly means of less than 30 mg/L and 45 mg/L, respectively; and pH between 6.0 and 9.0. Higher transitory levels of BOD up to 100 mg/L may be allowed under special circumstances, and treatment systems of less than 2 mgd may be exempt.[132]

Design Parameter Estimation

1. Reaction rate constant per day at 20°C (K_{20}). This term is used in design equations. It has not been determined for leachate, but its estimate for sewage treatment is between 0.5 and 1.0/day (averaging around 0.75/day).

2. Temperature correction coefficient (θ). Approximately 1.075.

3. Fraction of BOD removed for respiration (a) (not appearing in SS). Again estimated from sewage treatment as 0.9 to 1.4; the average is 1.1.

4. BOD feedback from bottom or sediment (F). Estimated summer at 20 percent (F = 1.2) and winter is 5 percent (F = 1.05).

Design Procedure

1. Select a rate constant (K) and adjust for summer and winter temperatures using the following relationship:

$$K_T = K_{20}\,\theta^{(T-20)} \qquad \text{[Eq 6]}$$

[130] D. G. Fenn et al.; E. R. Perrier and A. C. Gibson.
[131] E. S. K. Chian and F. B. DeWalle, Vol I.
[132] Metcalf and Eddy, Inc.

where: K_T = rate constant at desired temperature (T in ^oC)

K_{20} = rate constant at 20^oC

θ = temperature correction coefficient.

2. Calculate detention times to meet winter and summer efficiencies using the relationship:

$$\frac{S_e}{S_o} = \frac{F}{1 + K_t t} \qquad \text{[Eq 7]}$$

where: S_e = effluent soluble BOD required (mg/L)

S_o = influent BOD (after any dilution) (mg/L)

K_t = reaction rate constant at projected temperature

F = BOD sediment feedback

t = detention time (days).

Select the larger of the two detention times.

3. Calculate lagoon volume using the formula

$$V = Q_{max}\, t \qquad \text{[Eq 8]}$$

where: V = lagoon volume (m^3)

Q_{max} = maximum seasonal flow volume (m^3/day)

t = detention time (days)

4. Determine winter and summer oxygen requirement (kg/day). Fraction of BOD removed by respiration (a) must be assumed in following expression:

$$O_2 = a\, S_r\, QF \qquad \text{[Eq 9]}$$

where: O_2 = oxygen required (g/day)

a = fraction BOD removed by respiration

S_r = BOD removed, S_o-S_e (mg/L)

Q = flow rate (10^3 m^3/day)

F = BOD sediment feedback.

5. Aeration system size and energy requirements should not be determined from oxygen requirement and lagoon size. Horsepower required which will still allow solids to settle in from 0.01 to 0.02 hp/1000 gal.

6. The actual BOD in the effluent can be calculated from the soluble BOD in the effluent (S_e) and the amount of VSS in the effluent (all in mg/L):

$$\text{Actual BOD} = S_e + 0.3\ (\text{VSS}) \qquad [\text{Eq } 10]$$

The VSS can be estimated as 80 percent of the TSS in the effluent.

7. Optimum nutrient levels in the lagoon influent have been estimated as BOD:N:P = 100:5:1. Although nutrient additions to leachate treatment systems generally do not increase treatment efficiency, nutrient ranges in the leachate should be determined for future reference. Lime addition for ammonia stripping or metal removal will also precipitate phosphate and may cause a phosphorous deficiency in the system.

Example Calculations for Single Lagoon

Estimated leachate influent parameters:

1. BOD = 500 mg/L. This level of influent BOD can be reached by diluting the leachate with local makeup water, or by holding the leachate in a shallow equalization pond for 5 to 10 days before entry into facultative lagoon.

2. SS = 30 mg/L and 24 mg/L. Ferric iron oxide will add significantly to the total SS, but not to the VSS in the influent if the leachate has equilibrated with air over a period of time, or has been mixed with aerated makeup water. The iron oxide will end up in the sludge and will not have an appreciable effect on the effluent SS.

3. Nitrogen (as NH_3) = 75 mg/L in diluted or equalized influent. Phosphorous = 5 mg/L.

4. Lagoon temperature: summer 30°C, winter 10°C.

5. Desired effluent BOD = 30 mg/L.

6. Maximum leachate flow (Q_{max}) = 0.1 mgd.

7. Estimated design parameters:

a. Fraction of BOD removed by respiration (K_{20}) = 0.75/day.

b. Temperature correction coefficient (θ) = 1.075.

c. Fraction of BOD removed for respiration (a) = 1.1.

d. BOD feedback from sediment (F), summer = 1.2; winter = 1.05.

Calculations:

1. Adjust rate constant to actual lagoon temperatures:

a. Summer: $K_{30} = K_{20}\ \theta^{(T-20)} = 0.75\ (1.075)^{30-20} = 1.55$.

b. Winter: $K_{10} = 0.75\ (1.075)^{10-20} = 0.364.$

2. Calculate detention times for summer and winter:

a. Summer: $$\frac{S_e}{S_o} = \frac{F}{1 + K_{30}t}$$

$$\frac{30}{500} = \frac{1.2}{1 + 1.55_t}$$

$$t = 12 \text{ days}$$

b. Winter: $$\frac{30}{500} = \frac{1.05}{1 + 0.364t}$$

$$t = 45 \text{ days}$$

Thus, select maximum detention time of 45 days.

3. Calculate volume of lagoon:

$$V = Q_{max}t = 378(45) = 17 \times 10^3\ m^3\ (4.5 \times 10^6 \text{ gal})$$

This is equivalent to a 1.4-acre pond, 10-ft deep.

4. Calculate oxygen requirement (summer):

$$O_2 = a\ S_r\ QF = 1.1\ (500-30)\ (0.378)\ (1.2) = 234 \text{ kg/day.}$$

5. Estimate horsepower required for aeration:

$$(17 \times 10^3\ m^3)\ (4.5 \text{ hp}/10^3\ m^3) = 76.5 \text{ hp.}$$

6. Determine nutrient requirements (BOD:N:P = 100:5:1).

For BOD = 500 mg/L, N = 25 mg/L and P = 5 mg/L are required.

Multiple Facultative Lagoon Considerations

Two or three lagoons operated in series are preferable to the single, large pond discussed above. A reasonable and conservative design solution for multiple lagoons in series is simply to divide the single lagoon's size and depth into series or parallel multiple ponds suitable to the site.

Multiple lagoons greatly lessen the possibility of short circuits (which defeat the retention time design factor) and allow a certain amount of equalization of peak loads and volumes. Multiple ponds are also much more easily designed on sloping or irregular sites where transfer between lagoons can easily be made by gravity. However, dike and berm length are increased with multiple ponds.

6 CONCLUSIONS

The choice of appropriate treatment for landfill leachate should depend on leachate quality and discharge criteria. Young leachates (generated from landfills closed for 5 years or less) are best treated by biological treatment operations. Older leachates (generated from landfills closed for more than 5 years) are usually more amenable to physical/chemical forms of treatment. In many cases, a chain of unit operations must be applied to achieve the desired effluent quality. Equalization before treatment can increase process performance and reliability by preventing influent flow and concentration fluctuations. Including an equalization step in the treatment chain depends on the need for the function and the economic trade-off of sizing subsequent processes to meet peak flow depends.

Based on CERL's examination of specific treatment systems, it is concluded that:

1. Ammonia stripping is a sensitive, costly process which effectively reduces ammonia concentrations to levels acceptable for further biological treatment.

2. Carbon adsorption is an extremely versatile process which may be used as a polishing step for problem leachate constituents (PCBs, phenols, pesticides, toxic inorganics, chlorinated hydrocarbons, organic phosphorus, carbonates). In most cases, extensive pretreatment is required; this adds to the cost of an already expensive technology.

3. Chlorination is a reliable, economical means of disinfecting waste and provides coincidental oxidation of other compounds.

4. Ion exchange (solid) can polish leachates containing soluble metallic elements, halides, cyanides, acids -- such as carboxylics, sulfonics, and phenols -- and appropriate pHs. Upper limits for removal do exist. Overall ion exchange (solid) is an exceptionally sensitive, expensive technique requiring extensive pretreatment.

5. Ion exchange (liquid) removes inorganics to much higher concentrations than does ion exchange (solid). Costs and system sensitivities are similar in magnitude to conventional ion exchange.

6. Precipitation, flocculation, and sedimentation are effective methods of metal removal to certain limits. The governing factor is pH because it controls the solubility of the metal hydroxides formed during the process. Operation and maintenance costs are high because of the need for chemicals. Sludge is also a problem.

7. Reverse osmosis separates dissolved salts and some organics from the waste stream. The process requires extensive pretreatment and has high capital and operation and maintenance costs.

8. Wet air oxidation can handle high organic waste concentrations. Costs are proportional to the waste volume treated.

9. Activated sludge can treat most organic waste streams if a properly acclimated biological population is present. All versions of this system are costly (because of process configuration and separation), require highly skilled personnel to maintain proper function, and are sensitive to shock loadings.

10. Trickling filters and rotating biological discs are recommended as roughing or secondary processes for organic wastes. Rotating biological discs are the more flexible process.

11. Lagoons (aerobic, anaerobic, and facultative) show the most potential for treating young leachates. Lagoon technology is a straightforward, cost effective method of treating most sanitary landfill leachates.

CITED REFERENCES

Azad, Hardam, ed., Industrial Wastewater Management Handbook (McGraw-Hill, 1976).

Bastion, R. K., and S. C. Reed, Aquaculture Systems for Wastewater Treatment: Seminar Proceedings and Engineering Assessment, EPA-430/9-80-006 (U.S. Environmental Protection Agency, 1979), 485 pp.

Bechtel, Inc., A Guide to the Selection of Cost-Effective Wastewater Treatment Systems, Report No. PB-244-417 (U.S. Department of Commerce, 1975).

Benefield, L. D., and C. W. Randall, Biological Process Design for Wastewater Treatment (Prentice-Hall, Inc., 1980), 526 pp.

Boyle, W. C., and R. K. Ham, "Biological Treatability of Landfill Leachate," Journal of Water Pollution Control Federation, Vol 46, No. 5 (1974), pp 860-872.

Brunner, D. R., "Forecasting Production of Landfill Leachate," in Municipal Solid Waste: Land Disposal, Proceedings, 5th Annual Research Symposium, EPA-600/9-79-023a (U.S. Environmental Protection Agency, 1979), pp 268-282.

Cameron, R. D., and E. C. McDonald, "Coliforms and Municipal Landfill Leachate," Journal, Water Pollution Control Federation (December 1977), pp 2504-2505.

Chian, E. S. K., and F. B. DeWalle, "Sanitary Landfill Leachates and Their Treatment," Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers, Vol 102, EE2 (1976), pp 411-429.

Chian, E. S. K., and F. B. DeWalle, Evaluation of Leachate Treatment; Vol I: Characterization of Leachate, EPA-600/2-77-186a (U.S. Environmental Protection Agency, 1977), 226 pp.

Chian, E. S. K., and F. B. DeWalle, Evaluation of Leachate Treatment; Vol II: Biological and Physical-Chemical Processes, EPA-600/2-77-186b (U.S. Environmental Protection Agency, 1977), 265 pp.

Classifying Solid Waste Disposal Facilities, A Guidance Manual, SW-828 (U.S. Environmental Protection Agency, 1980), 187 pp.

Cook E. N., and E. G. Foree, "Aerobic Biostabilization of Sanitary Landfill Leachate," Journal of the Water Pollution Control Federation, Vol 46, No. 2, pp 380-392.

Culp, R. L., G. M. Wesner, and G. L. Culp, Handbook of Advanced Wastewater Treatment (Van Nostrand Reinhold Co., 1978).

Cummins, M. D., "Effect of Sanitary Landfill Leachate on the Activated Sludge Process," in Land Disposal: Municipal Solid Waste, Proceedings of 7th Research Symposium, EPA-600/9-81-002a (U.S. Environmental Protection Agency, 1981), pp 170-178.

De Renzo, D. H., Unit Operations for Treatment of Hazardous Industrial Wastes (Park Ridge, NJ: Noyes Data Corporation, 1978).

Eckenfelder, W. W., "Trickling Filter Design and Performance," Transactions of the American Society of Civil Engineers, Vol 128, Part III (1963), p 371.

Environmental Protection and Enhancement, AR 200-1 (HQ, DA, January 20, 1978).

Estimated Waste Treatment Costs, Vol 3: Cost Curves Applicable to 2500 gpd to 1.0 mgd Treatment Plants, EPA-600/2-79-162c (U.S. Environmental Protection Agency, 1979).

Estimating Waste Treatment Costs, Vol 3: Cost Curves Applicable to 2,500 gpd to 1.0 mgd Treatment Plants, EPA-600/2-79-162c (U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, 1979).

Fenn, D. G., K. J. Hanley, and T. V. DeGaere, Use of Water Balance Method for Predicting Leachate Generation From Solid Waste Disposal Sites, EPA-530/SW-168 (U.S. Environmental Protection Agency, 1975).

Foree, E. G., and V. M. Reed, Anaerobic Biological Stabilization of Sanitary Landfill Leachates, UTK TR65-73-CE 17 (University of Kentucky, 1973), 43 pp.

Fuller, W. H., Investigation of Landfill Leachate Pollution Attenuation by Soils, EPA-600/2-78-158 (U.S. Environmental Protection Agency, 1978), 239 pp.

Garland, G. A., and D. C. Mosher, "Leachate Effects of Improper Land Disposal," Waste Age (March 1975).

Germain, J. E., "Economic Treatment of Domestic Waste by Plastic-Medium Trickling Filters," Water Pollution Control Federation, Vol 28 (1966), p 192.

Gloyna, E. F., Waste Stabilization Ponds (Geneva, Switzerland: World Health Organization, 1971), 237 pp.

Graham, D. W., and D. S. Mavinic, "Biological Chemical Treatment of Leachate," in Environmental Engineering, Proceedings of 1979 National Conference (American Society of Civil Engineers, 1979), pp 291-299.

Griffin, R. A., and N. F. Shimp, Attenuation of Pollutants in Municipal Landfill Leachate by Clay Minerals, EPA-600/2-78-157 (U.S. Enviromental Protection Agency, 1978), 157 pp.

Hammer, M. J., Water and Wastewater Technology (John Wiley & Sons, 1975).

Handbook for Remedial Action at Waste Disposal Sites, EPA-625/6-82-006 (EPA, June 1982).

Ho, S., W. C. Boyle, and R. K. Ham, "Chemical Treatment of Leachates from Sanitary Landfills," Journal of Water Pollution Control Federation, Vol 46, No. 7 (1974), pp 1776-1791.

Industrial Pollution Control Systems (Rothschild, WI: Zimpro Environmental Control Systems, Inc., 1979).

Innovative and Alternative Technology Assessment Manual, EPA-430/9-78-009 (U.S. Environmental Protection Agency, Office of Water Program Operations, 1978).

Landon, R. A., "Utilization of a Mixing Zone for Leachate Management," in Land Application of Residual Materials, American Society of Civil Engineers (1979), pp 90-103.

Liptak, B. G., ed., Environmental Engineer's Handbook, Vol 1: Water Pollution (Chilton Book Company, 1974).

Lu, J. C. S., R. D. Morrison, and R. J. Stearns, "Leachate Production and Management from Municipal Landfills: Summary and Assessment," in Land Disposal: Municipal Solid Waste, EPA-600/9-81-002a (U.S. Environmental Protection Agency, 1981), pp 1-17.

Lutton, R. J., G. L. Regan, and L. W. Jones, Design and Construction of Covers for Solid Waste Landfills, EPA-600/2-79-165 (U.S. Environmental Protection Agency, 1979), 249 pp.

Malone, P. M., and L. W. Jones, Chemical and Physical Effects of Municipal Landfills on Underlying Soils and Groundwater, EPA-600/2-78-096 (U.S. Environmental Protection Agency, 1978), 154 pp.

Mather, J. R., and P. A. Rodriquez, The Use of the Water Budget in Evaluating Leachate Through Solid Waste Landfills, PB 80-180888 (Office of Water Research and Technology, U.S. Department of Commerce, 1978), 39 pp.

Menser, H. A., W. M. Winant, and O. L. Bennett, Spray Irrigation; a Land Disposal Practice for Decontaminating Leachates from Sanitary Landfills, ARR-NE-4 (U.S. Department of Agriculture, 1979), 48 pp.

Menser, H. A., et al., "The Utilization of Forage Grasses for Decontamination of Spray-Irrigated Leachate from a Municipal Landfill," Environmental Pollution, Vol 19 (1979), pp 249-260.

Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment, and Disposal (McGraw-Hill Book Company, 1979).

Metry, A., and F. L. Cross, Leachate Control and Treatment; Vol 7: Environmental Monograph Service (Westport, CT, Technomic Publishing Company, 1975), 58 pp.

Mikucki, W. J., E. D. Smith, R. Fileccia, J. Bandy, G. Gerdes, S. Kloster, G. Schanche, L. J. Benson, M. J. Staub, and M. A. Kamiya, Charateristics, Control, and Treatment of Leachate at Military Installations, Interim Report N-97/ADA097935 (U.S. Army Construction Engineering Research Laboratory, 1981).

Military Solid Waste Management, NAVFAC MO-213 (Department of the Navy, 1978).

Myers, T. E., N. R. Francingues, D. W. Thompson, and P. G. Malone, "Stabilized Industrial Waste in a Landfill Environment," in Disposal of Hazardous Waste; Proceedings of 6th Annual Research Symposium, EPA-600/9-80-010 (U.S. Environmental Protection Agency, 1980), pp 223-241.

Nemerow, N. L., Industrial Water Pollution: Origin, Characteristics and Treatment (Addison-Wesley Publishing Company, 1978).

Palit, T., and S. R. Qasim, "Biological Treatment Kinetics of Landfill Leachate," Journal of Environmental Engineer Division, Proceedings of the American Society of Civil Engineers, Vol 103, EE2 (1977), pp 353-366.

Perrier, E. R., and A. C. Gibson, Hydrological Simulation on Solid Waste Disposal Sites, SW-868 (U.S. Environmental Protection Agency, 1980), 111 pp.

Pettyjohn, W. A., et al., "Predicting Mixing of Leachate Plumes in Ground Water," in Land Disposal of Hazardous Waste, EPA-600/9-82-002 (U.S. Environmental Protection Agency, 1982), 549 pp.

Pohland, F. G., Sanitary Landfill Stabilization With Leachate Recycle and Residual Treatment, EPA-600/2-75-043 (U.S. Environmental Protection Agency, 1975), 116 pp.

Pohland, F. G., "Leachate Recycle at Landfill Management Option," Journal of Environmental Engineering, Proceedings of the American Society of Civil Engineers, Vol 106, EE6 (1980), pp 1057-1069.

Pollution Predicting Technique for Waste Disposal Siting, EPA-SW-162c (U.S. Environmental Protection Agency, 1978), 440 pp.

Reed, S. C., and R. K. Bastion, Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, EPA-430/9-80-007 (U.S. Environmental Protection Agency, 1980), 126 pp.

Remedial Action at Waste Disposal Sites (Office of Emergency and Remedial Response, U.S. Environmental Protection Agency), in press.

Robinson, H. D., and P. J. Marris, Leachate From Domestic Waste: Generation, Composition, and Treatment -- A Review, TR-108 (U. K. Water Research Center, 1979), p 38.

Rowe, A., "Tip Leachate Treatment by Land Irrigation," Solid Wastes, Vol 69, No. 12 (1979), pp 603-623.

Sanitary Landfill, ERIS Bulletin 81-05, TM 5-814-5 (U.S. Army Corps of Engineers, 1981).

Sanitary Landfill, Technical Manual (TM) 5-814-5 (Headquarters, Department of the Army, 1973).

Schulze, K. L., Conference on Biological Waste Treatment (Manhattan College, 1960).

Scott, M. P., "Leachate Treatment Options," Solid Waste Management (December 1981), pp 18-24.

Selected Biodegradation Techniques for Treatment and Ultimate Disposal of Organic Materials, EPA-600/2-79-006 (U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, 1979).

Stegmann, R., and H. J. Ehrig, "Operation and Design of Biological Leachate Treatment Plants," Prog. Water Tech. (Toronto), Vol 12 (1980), pp 919-947.

Steiner, R. L., et al., Demonstration of a Leachate Treatment Plant, PB-269-502 (Office for Solid Wastes, U.S. Environmental Protection Agency, 1977).

Stoll, B. J., "Demonstrating Leachate Treatment," in Municipal Solid Waste: Land Disposal, EPA-600/9-79-023a (U.S. Environmental Protection Agency, 1979), pp 313-323.

Ultoth, V. C., and D. S. Mavinic, "Aerobic Bio-Treatment of High-Strength Leachate," Journal of Environmental Engineer Divisions Proceedings, American Society of Civil Engineers, Vol 102, EE4 (1977), pp 647-661.

Wardell, J., M. Nielson, and J. Wong, "Contamination Control at Rocky Mountain Arsenal, Denver, Colorado," Management of Uncontrolled Hazardous Waste Sites (Silver Springs, MD: Hazardous Materials Control Research Institute, 1981), pp 374-379.

Wastewater Treatment Facilities for Sewered Small Communities, EPA-625/1-77-009 (U.S. Environmental Protection Agency, Technology Transfer Division, 1977).

Velz, C. J., "A Basic Law for Performance of Biological Beds," Sewage Works Journal, Vol 20 (1960), p 245.

Zapf-Gilje, R, and D. S. Mavinic, "Temperature Effects on Two-Stage Biotreatment of Leachate," Proceedings of American Society of Civil Engineers, Environmental Engineer Division, Specialty Conference on Environmental Engineering (1979), 825 pp.

UNCITED REFERENCES

Menser, H. A., W. M. Winant, O. L. Bennett, and P. E. Lundbent, "Decontamination of Leachate from a Sanitary Landfill by Spray Irrigation of a Forest Ecosystem," 1st Annual Conference of Applied Research and Practice on Municipal Industrial Waste (Madison, WI: University of Wisconsin, 1978), pp 585-600.

Permutit, Inc., Sulfex Heavy Metals Waste Treatment Process, Technical Bulletin 13:6.

Vermuelen, T., "Process Arrangements for Ion Exchange and Adsorption, Chemical Engineering Progress, Vol 10 (1977), pp 57-61.

APPENDIX:

BASIS OF COST ESTIMATES

The cost estimates presented in this appendix are intended to help solid waste management planners, decision makers, and design engineers. These people must select alternative onsite and offsite leachate treatment methods that will provide a designated level of treatment for leachates of various strengths and flow rates. The estimates are based directly on those derived by Chian and Dewalle and are updated to August 1977.[134]

The leachate flow rates and BOD_5 levels examined were 2 and 20 gal/min, and 5000 and 25 000 mg/L, respectively. These values were selected so that a broad range of leachates produced by various landfill sites could be considered. In view of the high BOD_5 levels and the objective of low treatment cost, biological processes were selected for first-stage treatment. Physical/chemical treatment processes would be used to treat the effluents from aerated lagoons and anaerobic filters.

There are certain limitations in using the cost estimates presented here. Estimates based on treatment data obtained from the laboratory studies and on average cost estimating data should be considered accurate enough to use only for general conclusions. When used with sound judgment by knowledgeable persons, the data can be useful in selecting appropriate treatment processes for a specific leachate with known levels of contamination and flow rates. It should also be realized that the cost estimates presented in this appendix must be revised and updated periodically since waste treatment costs change continually, and since new and improved waste treatment techniques and methodologies are rapidly emerging.

Addition to Activated Sludge Sewage Treatment Plant

The cost estimates for the combined treatment of leachate and municipal wastewater were based on the addition of leachate at a level of 1 percent by volume to the sewage when the nominal daily flow rate of the leachate is 30,000 gal (20 gpm). The proportion of leachate added was reduced to 0.1 percent by volume when its flow rate decreased to 3000 gal/day (2 gpm). If the leachate represents 1 percent of the flow into the municipal treatment plant, the overall flow rate of the plant must be 3 mgd.

The BOD_5 level of the municipal sewage introduced into the activated sludge system from the primary sedimentation basin is typically 140 mg/L. When 1 percent of leachate having a BOD_5 of 25 000 mg/L is added, the BOD_5 of the combined wastewater becomes 390 mg/L (140 + 1 percent of 25 000), corresponding to a 279 percent increase in sewage strength. To maintain the same effluent quality, the municipal treatment plant should therefore have the capacity to treat the equivalent of 8.4 mgd of sewage having a BOD_5 of 140 mg/L. A 280 percent decrease in sludge settling rate was also observed when

[134] E. S. K. Chian and F. B. DeWalle, Evaluation of Leachate Treatment; Vol II: Biological and Physical-Chemical Processes, EPA-600/2-77-186b (U.S. Environmental Protection Agency, 1977), 265 pp.

leachate was added at 1 percent. Again, to counteract this effect the municipal treatment plant facilities should be expanded to the equivalent of 8.4 mgd to maintain the same effluent quality. The increased treatment cost (resulting from the need for large aeration and sedimentation basins), greater air supply, larger anaerobic digesters, and increased sludge disposal are attributable to treating the specific leachate under study. The additional costs of transporting the leachate through pipelines and by trucking were also considered.

The calculations of the aeration basin volume requirements were based upon an F/M ratio of 0.3 day^{-1} and a MLVSS of 2000 mg/L. A yield of 0.65 g VSS/g BOD_5 was used for sewage and 0.80 g VSS/g BOD_5 for leachate. A factor of 0.8 was used to convert MLSS to VSS.

Cost figures based on the total costs of treating 1000 gal of sewage influent having a BOD_5 of 140 mg/L and at a specific plant capacity as given by Bechtel, Inc. were used to arrive at the costs for conventional activated sludge treatment, anaerobic digesters, and sludge drying.[135] A factor of 1.25 was then used to update the costs to August 1977. The costs of transporting leachate by pipeline were calculated assuming the use of 3-in.-diam, schedule-40 PVC pipe for a distance of 15 mi at an available pumping head of 75 psig. For smaller quantities of leachate, a trucking cost of 7.5¢/100 lb of liquid for a 30-mi round trip was used.

Aerated Lagoon

The design criteria for an aerated lagoon to treat leachate are as follows:

BOD_5 removal...........	99 percent
Mean cell residence time.................	90 days (BOD = 25 000 mg/L) 30 days (BOD = 5000 mg/L)
ML)VSS.................	8000 mg/L (BOD = 25 000 mg/L 6000 mg/L (BOD = 5000 mg/L)
Growth yield coefficient	0.8 g VVS/g BOD
Microorganism decay coefficent k_d).......	0.025 day^{-5}
Aerator................	2 lb oxygen/hp-hr under field conditions
BOD_5:P................	150:1
BOD_5:N................	20:1
Sludge production......	g VSS/0.8
Sedimentation basin....	400 gpd/sq ft

Design equations given in Wastewater Engineering were used to determine variables such as the volume of the aeration basins and the oxygen requirements.[136]

The capital (including engineering costs), operation, and maintenance costs were estimated. The installed costs of the basins were increased 15

[135]Bechtel, Inc., A Guide to the Selection of Cost-Effective Wastewater Treatment Systems, Report No. PB-244-417 (U.S. Department of Commerce, 1975).
[136]Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment, and Disposal (McGraw-Hill Book Co., 1979).

percent to cover the piping costs. The costs of ammonia and phosphoric acid were taken as of August 1977. Costs of \$120/ton for ammonia and \$3.20/100 lb for agriculture-grade phosphoric acid (52 to 54 percent available phosphoric acid) were used. The land cost was estimated at \$5000/acre. For electrical energy, a cost of 0.3¢/kWh was used. An average pay rate of \$10.00 per man-hour, including overhead costs, was used to estimate operating and maintenance costs. Capital equipment was depreciated on a straight-line basis over 10 years for moving equipment and 20 years for fixed installations. Interest charges were computed at the rate of 4 percent of the initial capital investment over the entire period.

Anaerobic Filter

The design criteria used for estimating the costs of treating leachate with an anaerobic filter were as follows:

BOD_5 removal...........	97 percent
Loading.................	0.31 kg BOD_5/g BOD_5
Yield, VSS.............	0.024 g/VSSg BOD_5
Detention time	87 days (leachate BOD = 25 000 mg/L)
....	16 days (leachate BOD = 5000 mg/L)
Recirculation ratio....	20:1
Yield, methane.........	1.75 (78 percent CH4)/g TOC

The capital investment estimate was based on the use of a rubber-lined steel tank and vinyl core packings, and equipment such as pumps and piping. The operating costs were computed in the same way as for the aerated lagoon; the maintenance costs used, however, were 5 percent of the capital investment on an annual basis.

Slow Sand Filtration

The cost estimates for the slow sand filtration unit were based on a single data point: a unit of comparable capacity installed recently (1977). A rather conservative flow rate of 8 gal/day-sq ft was used in the design of the filter. The operating and maintenance costs were calculated using the previously described methods of computing costs such as depreciation, interest, and maintenance.

Activated Carbon

Based on both the batch isotherm and the column data, the design criteria for the activated carbon unit were as follows:

Influent TOC*..........	200 mg/L from aerated lagoon (AL)
....	600 mg/L from anaerobic filter (AF)
TOC removal............	75 percent
Color removal..........	*90 percent at 400 nanomicrons*
(X/M)..................	0.15 g TOC/g carbon (AL)**
....	0.10 g TOC/g carbon (AF)
Activated carbon.......	Filtrasorb 400
Contact time...........	2 hour
Pretreatment...........	Slow sand filter

The capital investment was estimated by extrapolating the cost data provided by Bechtel, Inc.[137] After being updated to August 1977, this cost was \$1.0/1000 gal. The operation and maintenance costs were also obtained from Bechtel, Inc.[138] The cost of activated carbon used was \$0.65/lb.

Reverse Osmosis

The design criteria for the reverse osmosis process were as follows:

Pretreatment...........	Slow sand filtration, activated carbon column, 5 prefilter
Product water recovery.	90 percent
TDS removal............	95 percent
TOC removal............	80 percent
Module.................	*DuPont Hollow Fiber*
Pressure...............	600 psig

The cost estimates for reverse osmosis using DuPont's B-10 modules were based on average cost data obtained from the manufacturers as of August 1977. Average costs of \$1.67/gpd and \$3.33/gpd were used for the 30,000 and 3000-gpd plants, respectively. The power requirements are 20 hp for a 30,000-gpd unit and 2 hp for a 3000-gpd unit. Unlike activated carbon treatment processes, operating costs for reverse osmosis treatment are relatively insensitive to the levels of contaminants in the feed. The depreciation costs are based on 10-year life for the mechanical parts and a 3-year life for the membrane modules. Other costs for operation and maintenance are similar to those used in the previous calculations.

---

*The influent TOC will be 1/5 of this with a leachate having a BOD_5 of 5000 mg/L instead of 25 000 mg/L.

**X = impurity adsorbed; M = weight of carbon required.

[137]Bechtel, Inc., A Guide to the Selection of Cost-Effective Wastewater Treatment Systems, Report No. PB-244-417 (U.S. Department of Commerce, 1975).

[138]Bechtel, Inc., Guide.

METRIC CONVERSION CHART

1 acre	= 0.4 ha
1 ft	= 0.3 m
1 cu ft	= 28.3 L
1 cfm/1000 gal	= 7.5×10^{-3} m^3/m^3/min
1 yd	= 0.9 m
1 gal	= 3.79 L
1 gpm	= 6.3090×10^{-2} L/sec
1 mgd	= 3.79×10^{3} m^3/day
1 hp	= 0.75 kW
hp/1000 gal	= 0.1970 kW/m^3
1 lb	= 0.45 kg
1 oz	= 28.3 g
1 psi	= 6.9 kPa
1 psig	= 6.9 kPa
1 yd	= 0.9 m
1 ton	= 0.9 MT
1 sq yd	= 0.8 m^2
$\frac{{}^{o}F-32}{1.8}$	= ^{o}C

CERL Distribution

Chief of Engineers
ATTN: Tech Monitor
ATTN: DAEN-ASI-L (2)
ATTN: DAEN-CCP
ATTN: DAEN-CW
ATTN: DAEN-CWE
ATTN: DAEN-CWR-W
ATTN: DAEN-CWO
ATTN: DAEN-CWP
ATTN: DAEN-EC
ATTN: DAEN-ECC
ATTN: DAEN-ECE
ATTN: DAEN-ZCF
ATTN: DAEN-ECB
ATTN: DAEN-RD
ATTN: DAEN-RDC
ATTN: DAEN-RDM
ATTN: DAEN-RM
ATTN: DAEN-ZCZ
ATTN: DAEN-ZCE
ATTN: DAEN-ZCI
ATTN: DAEN-ZCM

FESA, ATTN: Library 22060

FESA, ATTN: DET III 79906

US Army Engineer Districts
ATTN: Library
Alaska 99501
Al Batin 09616
Albuquerque 87103
Baltimore 21203
Buffalo 14207
Charleston 29402
Chicago 60604
Detroit 48231
Far East 96301
Fort Worth 76102
Galveston 77550
Huntington 25721
Jacksonville 32232
Japan 96343
Kansas City 64106
Little Rock 72203
Los Angeles 90053
Louisville 40201
Memphis 38103
Mobile 36628
Nashville 37202
New England 02154
New Orleans 70160
New York 10007
Norfolk 23510
Omaha 68102
Philadelphia 19106
Pittsburgh 15222
Portland 97208
Riyadh 09038
Rock Island 61201
Sacramento 95814
San Francisco 94105
Savannah 31402
Seattle 98124
St. Louis 63101
St. Paul 55101
Tulsa 74102
Vicksburg 39180
Walla Walla 99362
Wilmington 28401

US Army Engineer Divisions
ATTN: Library
Europe 09757
Huntsville 35807
Lower Mississippi Valley 39180
Middle East 09038
Middle East (Rear) 22601
Missouri River 68101
North Atlantic 10007
North Central 60605
North Pacific 97208
Ohio River 45201
Pacific Ocean 96858
South Atlantic 30303
South Pacific 94111
Southwestern 75202

US Army Europe
HQ, 7th Army Training Command 09114
ATTN: AETTG-DEH (5)
HQ, 7th Army ODCS/Engr. 09403
ATTN: AEAEN-EH (4)
V. Corps 09079
ATTN: AETVDEH (5)
VII. Corps 09154
ATTN: AETSDEH (5)
21st Support Command 09325
ATTN: AEREH (5)
Berlin 09742
ATTN: AEBA-EN (2)
Southern European Task Force 09168
ATTN: AESE-ENG (3)
Installation Support Activity 09403
ATTN: AEUES-RP

8th USA, Korea
ATTN: EAFE (8) 96301
ATTN: EAFE-Y 96358
ATTN: EAFE-ID 96224
ATTN: EAFE-4M 96208

8th USA, Korea
ATTN: EAFE-H 96271
ATTN: EAFE-P 96259
ATTN: EAFE-T 96212

ROK/US Combined Forces Command 96301
ATTN: EUSA-HHC-CFC/Engr

USA Japan (USARJ)
Ch, FE Div, AJEN-FE 96343
Fac Engr (Honshu) 96343
Fac Engr (Okinawa) 96331

Rocky Mt. Area 80903

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

Western Area Office, CE
Vanderberg AFB, CA 93437

416th Engineer Command 60623
ATTN: Facilities Engineer

US Military Academy 10996
ATTN: Facilities Engineer
ATTN: Dept of Geography & Computer Science
ATTN: DSCPER/MAEN-A

Engr. Studies Center 20315
ATTN: Library

AMMRC, ATTN: DRXMR-WE 02172

USA ARRCOM 61299
ATTN: DRCIS-RI-I
ATTN: DRSAR-IS

DARCOM - Dir., Inst., & Svcs.
ATTN: Facilities Engineer
ARRADCOM 07801
Aberdeen Proving Ground 21005
Army Matls. and Mechanics Res. Ctr.
Corpus Christi Army Depot 78419
Harry Diamond Laboratories 20783
Dugway Proving Ground 84022
Jefferson Proving Ground 47250
Fort Monmouth 07703
Letterkenny Army Depot 17201
Natick R&D Ctr. 01760
New Cumberland Army Depot 17070
Pueblo Army Depot 81001
Red River Army Depot 75501
Redstone Arsenal 35809
Rock Island Arsenal 61299
Savanna Army Depot 61074
Sharpe Army Depot 95331
Seneca Army Depot 14541
Tobyhanna Army Depot 18466
Tooele Army Depot 84074
Watervliet Arsenal 12189
Yuma Proving Ground 85364
White Sands Missile Range 88002

DLA ATTN: DLA-WI 22314

FORSCOM
FORSCOM Engineer, ATTN: AFEN-FE
ATTN: Facilities Engineer
Fort Buchanan 00934
Fort Bragg 28307
Fort Campbell 42223
Fort Carson 80913
Fort Devens 01433
Fort Drum 13601
Fort Hood 76544
Fort Indiantown Gap 17003
Fort Irwin 92311
Fort Sam Houston 78234
Fort Lewis 98433
Fort McCoy 54656
Fort McPherson 30330
Fort George G. Meade 20755
Fort Ord 93941
Fort Polk 71459
Fort Richardson 99505
Fort Riley 66442
Presidio of San Francisco 94129
Fort Sheridan 60037
Fort Stewart 31313
Fort Wainwright 99703
Vancouver Bks. 98660

HSC
ATTN: HSLO-F 78234
ATTN: Facilities Engineer
Fitzsimons AMC 80240
Walter Reed AMC 20012

INSCOM - Ch, Instl. Div.
ATTN: Facilities Engineer
Arlington Hall Station (2) 22212
Vint Hill Farms Station 22186

MDW
ATTN: Facilities Engineer
Cameron Station 22314
Fort Lesley J. McNair 20319
Fort Myer 22211

MTMC
ATTN: MTMC-SA 20315
ATTN: Facilities Engineer
Oakland Army Base 94626
Bayonne MOT 07002
Sunny Point MOT 28461

NARADCOM, ATTN: DRDNA-F 071160

TARCOM, Fac. Div. 48090

TRADOC
HQ, TRADOC, ATTN: ATEN-FE
ATTN: Facilities Engineer
Fort Belvoir 22060
Fort Benning 31905
Fort Bliss 79916
Carlisle Barracks 17013
Fort Chaffee 72902
Fort Dix 08640
Fort Eustis 23604
Fort Gordon 30905
Fort Hamilton 11252
Fort Benjamin Harrison 46216
Fort Jackson 29207
Fort Knox 40121
Fort Leavenworth 66027
Fort Lee 23801
Fort McClellan 36205
Fort Monroe 23651
Fort Rucker 36362
Fort Sill 73503
Fort Leonard Wood 65473

TSARCOM, ATTN: STSAS-F 63120

USACC
ATTN: Facilities Engineer
Fort Huachuca 85613 (2)
Fort Ritchie 21719

WESTCOM
ATTN: Facilities Engineer
Fort Shafter 96858
ATTN: APEN-IM

SHAPE 09055
ATTN: Survivability Section, CCB-OPS
Infrastructure Branch, LANDA

HQ USEUCOM 09128
ATTN: ECJ 4/7-LOE

Fort Belvoir, VA 22060
ATTN: ATZA-DTE-EM
ATTN: ATZA-DTE-SW
ATTN: ATZA-FE
ATTN: Engr. Library
ATTN: Canadian Liaison Office (2)
ATTN: IWR Library

Cold Regions Research Engineering Lab 03755
ATTN: Library

ETL, ATTN: Library 22060

Waterways Experiment Station 39180
ATTN: Library

HQ, XVIII Airborne Corps and 28307
Ft. Bragg
ATTN: AFZA-FE-EE

Chanute AFB, IL 61868
3345 CES/DE, Stop 27

Norton AFB 92409
ATTN: AFRCE-MX/DEE

Tyndall AFB, FL 32403
AFESC/Engineering & Service Lab

NAFEC
ATTN: RDT&E Liaison Office
Atlantic Division 23511
Chesapeake Division 20374
Southern Division 29411
Pacific Division 96860
Northern Division 19112
Western Division 64066
ATTN: Sr. Tech. FAC-03T 22332
ATTN: Asst. CDR R&D, FAC-03 22332

NCEL 93041
ATTN: Library (Code L08A)

Defense Technical Info. Center 22314
ATTN: DDA (12)

Engineering Societies Library 10017
New York, NY

National Guard Bureau 20310
Installation Division

US Government Printing Office 22304
Receiving Section/Depository Copies (2)

US Army Env. Hygiene Agency
ATTN: HSHB-E 21010

ENE Team Distribution

Chief of Engineers
ATTN: DAEN-ZCF-B
ATTN: DAEN-ZCF-U
ATTN: DAEN-ECZ-A

US Army Engineer District
New York 10007
ATTN: Chief, NANEN-E
ATTN: Chief, Design Br.
Pittsburgh 15222
ATTN: Chief, Engr Div
Philadelphia 19106
ATTN: Chief, NAPEN-E
Norfolk 23510
ATTN: Chief, NAOEN-D
Huntington 25721
ATTN: Chief, ORHED-H
Wilmington 28401
ATTN: Chief, SAWEN-PM
ATTN: Chief, SAWEN-E
Charleston 29402
ATTN: Chief, Engr Div
Savannah 31402
ATTN: Chief, SASAS-L
Jacksonville 32232
ATTN: Env Res Br
Mobile 36628
ATTN: Chief, SAMEN-C
Vicksburg 39180
ATTN: Chief, Engr Div
Louisville 40201
ATTN: Chief, Engr Div
St. Paul 55101
ATTN: Chief, ED-H
Chicago 60604
ATTN: Chief, NCCCO-R
ATTN: Chief, NCCED-H
ATTN: Chief, NCCPD-ER
ATTN: Chief, NCCPE-PES
St. Louis 63101
ATTN: Chief, ED-B
ATTN: Chief, ED-D
Kansas City 64106
ATTN: Chief, Engr Div
Omaha 68102
ATTN: Chief, Engr Div
Little Rock 72203
ATTN: Chief, Engr Div
Tulsa 74102
ATTN: Chief, Engr Div
Fort Worth 76102
ATTN: Chief, SWFED-D
ATTN: Chief, SWFED-MA/MR
Galveston 77550
ATTN: Chief, SWGAS-L
ATTN: Chief, SWGCO-M
Los Angeles 90053
ATTN: Chief, SPLED-E
San Francisco 94105
ATTN: Chief, Engr Div
Sacramento 95814
ATTN: Chief, SPKED-D
Far East 96301
ATTN: Chief, Engr Div
Seattle 98124
ATTN: Chief, NPSEN-FM
ATTN: Chief, EN-DB-SE
ATTN: Chief, NPSEN-PL-WC
ATTN: Chief, NPSEN-PL-ER
Walla Walla 99362
ATTN: Chief, Engr Div
Alaska 99501
ATTN: Chief, NPASA-R

US Army Engineer Division
New England 02154
ATTN: Chief, NEDED-E
North Atlantic 10007
ATTN: Chief, NADEN-T
Middle East (Rear) 22601
ATTN: Chief, MEDED-T
South Atlantic 30303
ATTN: Chief, SADEN-TE

US Army Engineer Division
Huntsville 35807
ATTN: Chief, HNDED-CS
ATTN: Chief, HNDED-ME
ATTN: Chief, HNDED-SR
Lower Mississippi Valley 39180
ATTN: Chief, PD-R
Ohio River 45201
ATTN: Chief, Engr Div
North Central 60605
ATTN: Chief, Engr Planning Br
Missouri River 68101
ATTN: Chief, MRDED-T
Southwestern 75242
ATTN: Chief, SWDED-TH
North Pacific 97208
ATTN: Chief, Engr. Div.
South Pacific 94111
ATTN: Chief, SPDED-TG
ATTN: Laboratory
Pacific Ocean 96858
ATTN: Chief, Engr Div
ATTN: Chief, PODED-MP
ATTN: Chief, PODED-P

5th US Army 78234
ATTN: AFKB-LG-E

6th US Army 94129
ATTN: AFKC-EN

7th US Army 09407
ATTN: AETTM-HRD-EHD

10th Medical Laboratory
APO New York 09180

US Army Foreign Science & Tech Center
ATTN: Charlottesville, VA 22901
ATTN: Far East Office 96328

USA ARRADCOM
ATTN: DRDAR-LCA-OK

West Point, NY 10996
ATTN: Dept of Mechanics
ATTN: Library

Ft. Belvoir, VA 22060
ATTN: Learning Resources Center
ATTN: ATSE-TD-TL (2)

Ft. Clayton Canal Zone 34004
ATTN: DFAE

Ft. A. P. Hill 24502
ATTN: FE

Ft. Leavenworth, KS 66027
ATTN: ATZLCA-SA

Ft. Lee, VA 23801
ATTN: DRXMC-D (2)

Ft. McPherson, GA 30330
ATTN: AFEN-CD

Ft. Monroe, VA 23651
ATTN: ATEN-AD (3)
ATTN: ATEN-FE-E
ATTN: ATEN-FE-U

Aberdeen Proving Ground, MD 21005
ATTN: AMXHE
ATTN: HSE-EW
ATTN: DAC-ARI-E

Naval Facilities Engr Command 22332
ATTN: Code 04

US Naval Oceanographic Office 39522
ATTN: Library

Naval Training Equipment Center 32813
ATTN: Technical Library

Port Hueneme, CA 93043
ATTN: Morell Library

Bolling AFB, DC 20330
AF/LEEEU

WASH DC 20330
AF/RDXT

Little Rock AFB
ATTN: 314/DEEE

Patrick AFB, FL 32925
ATTN: XRQ

Tinker AFB, OK 73145
2854 ABG/DEEE

Tyndall AFB, FL 32403
AFESC/PRT

Bldg Research Advisory Board 20418

Dept of Transportation
Tallahassee, FL 32304

Dept of Transportation Library 20590

Transportation Research Board 20418

Airports and Construction Services Dir
Ottawa, Ontario, Canada K1A 0N8

Division of Building Research
Ottawa, Ontario, Canada K1A 0R6

National Defense Headquarters
Ottawa, Ontario, Canada K1A 0K2

105
1-83

Treatment of landfill leachate at Army facilities / by R. A. Shafer ...(et al.) - Champaign, IL : Construction Engineering Research Laboratory ; available from NTIS, 1983.
131 p. (Technical report / Construction Engineering Research Laboratory ; N-155)

1. Sanitary landfills - leaching. I. Shafer, R. A. II. Smith, Edgar D. III. Bandy, John T. IV. Malone, P. G. V. Moore, D. A. VI. Jones, L. W. VII. Series : Technical report (Construction Engineering Research Laboratory) ; N-155.

LMED

8